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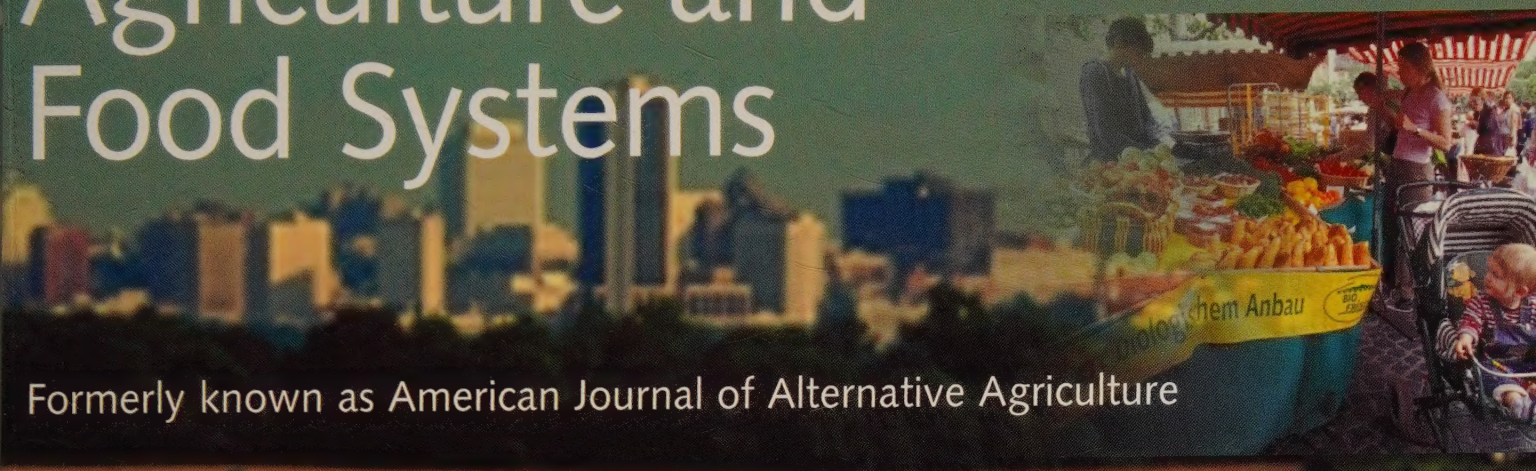

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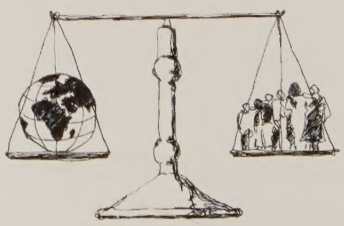

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New roller crimper concepts for mechanical termination of cover crops in conservation agriculture

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Abstract

Rollers crimpers have been used in conservation agriculture to terminate cover crops; however, excessive vibration generated by the original straight-bar roller design has delayed adoption of this technology in the United States. To avoid excessive vibration, producers generally reduce operating speeds that increase the time needed to perform the field operation. The objectives of this research were to identify roller crimper designs that terminated rye cover crops consistently, resulted in soil moisture conservation after use, and minimized vibrations when operated in the field. Six different roller types were developed and tested at 3.2 and 6.4 km h^{-1} in Alabama field experiments during the 2006, 2007 and 2008 growing seasons. All roller types were used alone and one also in combination with glyphosate. Rye mortalities were evaluated 1, 2 and 3 weeks after rolling and compared with the check (non-rolled standing rye). Soil volumetric moisture content (VMC) was measured at the day of rolling, and then at 1, 2 and 3 weeks after rolling. Vibration was measured on the rollers' and tractor's frames during operation. Mortality for rolled rye 2 weeks after rolling was at least 98% compared with 96% for the check in 2006, 93% for rolling compared with 75% for the check in 2007, and 94% for rolling compared with 60% for the check in 2008 ($P < 0.10$). There were no consistent differences in rye mortality across roller types (without glyphosate) and speeds. VMC for soil in non-rolled rye plots was consistently lower than in rolled rye plots, averaging 3% compared with 7% 2 weeks after rolling in 2006, and 4% compared with 8% in 2008. During 2007, VMC was affected by severe drought conditions, and differences between roller treatments were detected but minor. The straight-bar roller generated the highest vibration on the tractor's frame at 6.4 km h^{-1} (0.71 m s^{-2}, RMS), which exceeded International Standards (International Standard Office (ISO)). At 6.4 km h^{-1}, new roller designs generated significantly lower acceleration levels from 0.12 to 0.32 m s^{-2} on the tractor's frame and were below detrimental effects on health 'health limits' classified by ISO. Overall, 2 weeks after rolling, all roller designs effectively terminated rye above 90%, which is the recommended termination level of rye to plant a cash crop into residue mat, while protecting soil surface from water loss. New roller designs generate less vibration than the original design and can be used safely at higher operating speeds.

Key words: cover crops, roller crimper, mechanical kill, termination rate, conservation system

Introduction

Cover crops are an essential part of many conservation tillage systems, but they have to be managed appropriately to obtain their full benefit[1,2]. In the southern United States, cereal rye (*Secale cereale* L.) is commonly used as a winter cover crop. Mechanical rollers have been used in some conservation systems to terminate cover crops[3], but excessive vibration and low operating speeds associated with current roller designs have contributed to a low rate of adoption by US farmers[4].

In some conservation systems, especially in the southeastern US, terminating cover crops 3 weeks prior to planting the cash crop is a standard agricultural extension recommendation[1]. Termination is achieved mainly by the use of herbicides, since spraying is relatively fast and effective. The effectiveness of different mechanical termination methods for cover crops without using herbicides was considered in a previous research. The performance of an undercutter in terminating cover crops by severing the roots of cover crops while flattening the plants for subsequent weeds suppression was considered in one study[5]. Although cover crop mortalities following an undercutter were high (95%), the process disturbed soil, was slow, and required more power compared with other termination methods[6]. Creamer and Dabney[6] evaluated

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various cover crop kill methods such as residue incorporation by disking, flail mowing, mowing, undercutting, rolling chopping and rolling. They concluded that rolling alone using a rolling basket without crimping bars was less effective in killing cover crops compared with undercutting. However, compared with cover crop incorporation, rolling and other termination methods that maintained residue on the soil surface provided much better weed suppression.

Mowing and most other methods for terminating cover crops mechanically rely on detaching aboveground cover crop vegetation from the roots and mixing, chopping and shredding residue on the soil surface. However, for a cover crop such as rye that is relatively tall and can lodge in multiple directions, planting efficiency can be reduced due to a need for frequent stops to clean accumulated cover crop residue stuck in the planting units. In addition, non-rolled residue may cause 'hair-pinning', a condition where lodged residue prevents adequate seed-soil contact, thus reducing a cash crop stand. Mowing of cover crops especially in early growth stages may trigger significant re-growth. Wilkins and Bellinder[7] studied re-growth of rye and wheat after mowing at different plant growth stages. They found that when rye was mowed at the first node growth stage (Zadoks growth stage = 31; Zadoks et al.[8]), re-growth biomass was 4340 and 8470 kg ha^{-1}, 4 and 8 weeks after mowing, respectively. These findings indicate that after mowing at vegetative growth stages, rye cover crops still compete for nutrients and water resources in spring when cash crops are planted. Rye cover crop termination should be delayed until near-maximum biomass production for full soil coverage and to ensure minimal potential for re-growth is assured.

The practice of using rollers/crimpers to terminate cover crops mechanically without herbicides originated in Brazil[3]. This technology is receiving increased attention in the United States. Ashford and Reeves[1] indicated that when rolling was conducted at the appropriate plant growth stage (i.e., early milk to soft dough, Zadoks growth stages 70–85); rollers were as effective as synthetic herbicides at terminating a cover crop (94%). They concluded that rye mortality above 90% was sufficient to begin cash crop planting due to accelerated rye senescence[1]. Another important aspect of rolling cover crops is that a flat mat is created that lies in the direction of travel. The cover crop planting operation can then be conducted in a direction parallel to the rolled cover crop. This allows proper plant establishment by minimizing interference between the residue and planter.

Some North American producers have reported problems with roller implements[4,9]. The main complaint has been the excessive vibration generated by the rollers. Vibration generated during the roller crimper operation is related to crimping frequencies, firmness and uniformity of the soil surface, and roller design/quality of fabrication. The types of vibration that producers most complain about are generated from the crimping action by the original straight bar roller design[9]. Research has shown that vibration generated by agricultural equipment can have detrimental effects on the operator's health, including increased heart rate, headache, stomach pain, lower back pain and long-term vibration exposure, leading to spinal degeneration[10–12]. The International Standard Office (ISO)[13] developed vibration limits that are harmful to the human body. Vibration between 0.5 and 1.0 m s^{-2} is classified as 'fairly uncomfortable' and from 0.8 to 1.6 m s^{-2} is considered 'uncomfortable'. Vibration above 2.0 m s^{-2} is described as 'extremely uncomfortable'. Australian Standards developed limits for 8-h human exposure to vibration; for comfort limit, fatigue limit and health limit (detrimental effect) vibrations levels should be 0.1, 0.315 and 0.63 m s^{-2}, respectively[14].

The most effective method of alleviating roller vibration has been to reduce travel speed. Previous research[9] evaluated vibrations transferred to a tractor's frame from 1.8-m wide original straight bar roller design. When operating speed was reduced from 8 to 4.8 km h^{-1}, vibration on the tractor frame was reduced 8 times, from 5.7 to 0.7 m s^{-2}. However, most US producers find speed reduction to be an unacceptable solution due to the much higher operating speeds that they were able to use previously when spraying herbicides onto cover crops.

To address vibration problems generated by the original straight bar roller, in 2004 a new family of rollers was developed at the National Soil Dynamics Laboratory (NSDL). The first concept was a cylindrical roller with curved or elliptical crimping bars[4], and the second was a smooth roller drum with an oscillating crimping bar providing ten crimps per revolution. Results from previous research that compared the original roller design with a curved bar roller and a smooth roller with crimping bar showed that these rollers generated significantly less vibration compared with the original concept while maintaining high termination rates for cover crops[9]. In 2006, two additional roller designs were developed: a modified smooth roller crimper providing eight crimps per revolution and a two-stage roller crimper to offer effective roller solutions needed by smaller farming communities. The present research evaluated performance of all rollers developed at the NSDL during 2004–2008.

Six roller types were tested to determine their effect on cover crop mortality, soil volumetric water content and vibration. The specific objectives were to determine: (1) the effectiveness of different roller designs for terminating a rye cover crop; (2) the operating speed effect on mortality for different roller designs; (3) rye rolling/crimping effects on soil volumetric moisture content (VMC); and (4) vibration levels generated by different roller designs at different operating speeds.

Materials and Methods

Six 1.8-m wide rollers developed at the NSDL were compared in replicated field experiments during 2006, 2007

Figure 1. Smooth drum roller.

Figure 2. Straight bar roller crimper.

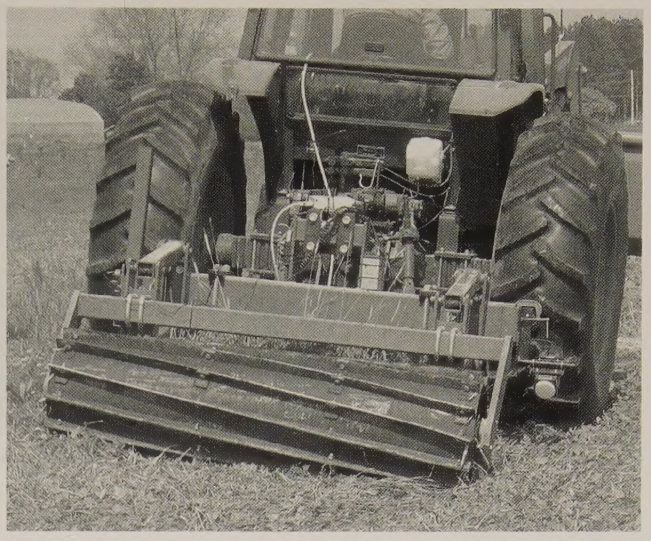

Figure 3. Curved bar roller crimper.

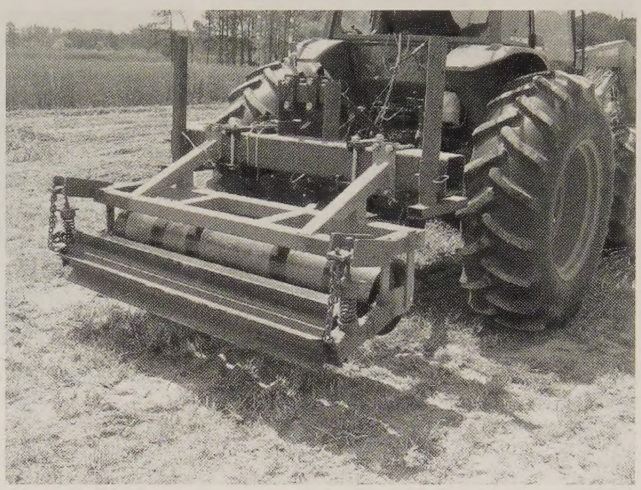

Figure 4. Two-stage roller crimper.

and 2008 at the Alabama Agricultural Experiment Station's E.V. Smith Research Station on a Compass loamy sandy soil (thermic Plinthic Paleudults) near Auburn, Alabama, USA. Rollers utilized in the experiment were: a smooth drum with and without glyphosate (Roundup^{TM}, WeatherMax) (Fig. 1), a roller with straight bars (Fig. 2), a roller with curved bars (Fig. 3), a new two-stage roller (Fig. 4), a smooth roller crimper with an original cam mechanism (Fig. 5a) and a new smooth roller crimper with a modified cam mechanism (Fig. 5b). The two-stage roller and the smooth roller crimper with the modified cam mechanism (patent pending) were developed for the 2006 growing season. The two-stage roller crimper is comprised of a smooth drum that functions to flatten the cover crop and serves as a vibration damper (generated by the second drum). The second drum has six crimping bars and is preloaded by two springs for more effective crimping. This roller is suitable for smaller farming operations, i.e., vegetable farms where producers have smaller tractors with less horsepower. The modified smooth roller with an oscillating crimping bar provides more aggressive crimping action compared with the original cam design. It provides eight crimps per revolution (instead of ten crimps provided by the original cam mechanism) to generate more aggressive crimping action. This results from the unique geometry of the cam mechanism and patented crimping bar design, which accounts for non-uniform soil surfaces across the crimping width. Rollers were tested at operating speeds of 3.2 and 6.4 km h^{-1}. The 6.4 km h^{-1} speed was chosen to match speeds commonly used in field chemical applications.

All six roller designs were evaluated alone and, in addition, the smooth drum roller without crimping bars was evaluated in combination with glyphosate applied at the rate of 1.12 kg ha^{-1} (active ingredient), with spraying following the rolling operation on the same day. Non-rolled rye was used as a control (check). The treatments were replicated four times and arranged in a randomized complete block design. Each experimental unit was 15-m long

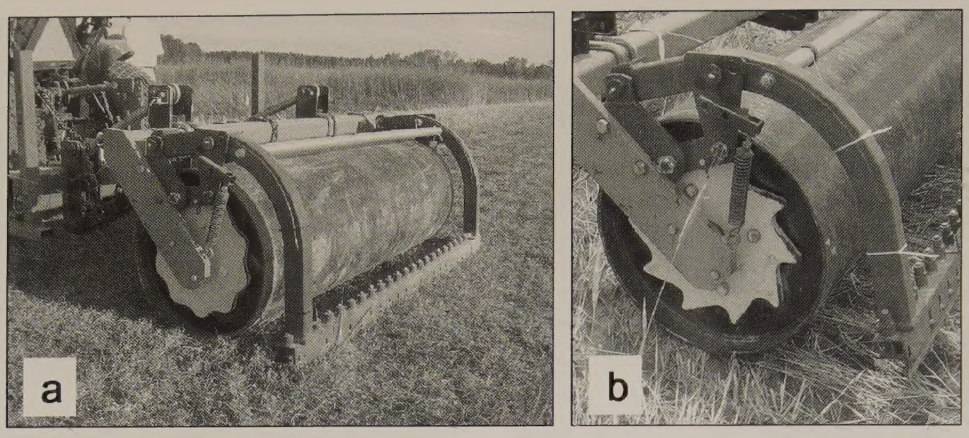

Figure 5. Smooth roller crimper: (a) original cam and (b) modified cam mechanism.

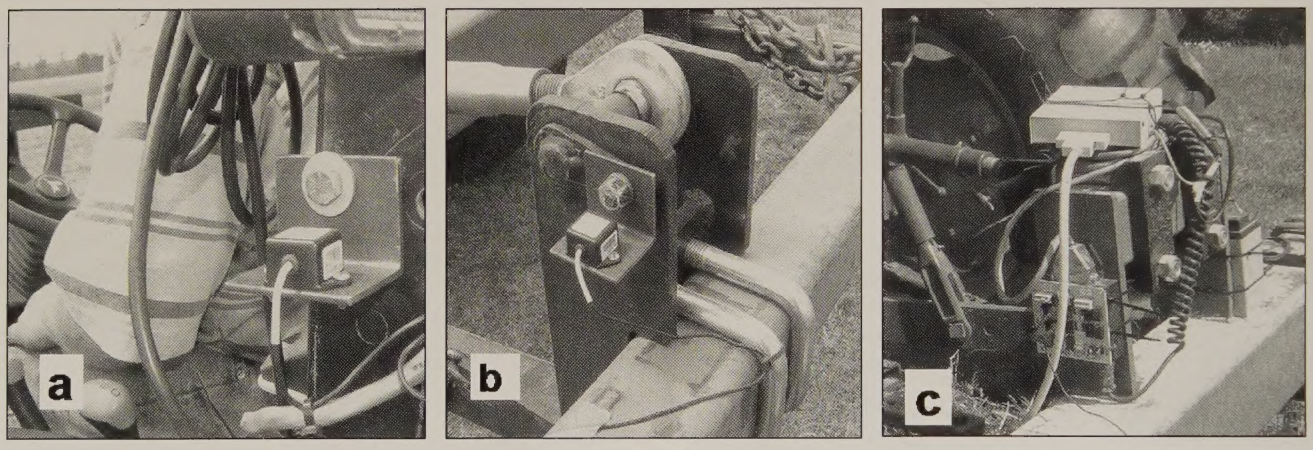

Figure 6. Placement of one-dimensional (*z*-axis) accelerometer from Crossbow Technology: (a) tractor frame, (b) roller frame, and (c) 'on board' data acquisition system.

and 1.8-m wide. 'Elbon' winter rye was drilled in the fall of 2005 (November 3), 2006 (October 25) and 2007 (November 15) using a John Deere 1700 grain drill at a seeding rate of 95 kg ha^{-1}. To optimize rye growth, ammonium nitrate (33-0-0) was broadcast onto the cover crop at a rate of 33 kg ha^{-1} N during both mid-November and mid-February. Rye plants were rolled at the soft dough growth stage (Zadoks growth stage 85) in 2006 (April 18), and at the early milk growth stage (Zadoks growth stage 73) in both 2007 (April 17) and 2008 (April 21). The rye was rolled parallel to the direction that the cover crop was seeded.

VMC was measured the day of rolling and after the first, second and third week using a portable TDR moisture meter from Spectrum Technologies (Plainfield, Illinois). The sensor was equipped with 12-cm long rods and was inserted vertically into the soil surface. The length of rods was selected to measure soil VMC at a shallow depth, available for germination of cash crop seeds planted into the residue cover. Five readings were taken close to the middle of each plot at marked locations spaced about 2.5 m apart.

Accelerometers from Crossbow Technology Inc. (San Jose, California) were mounted on the tractor frame to measure vibration levels to which the driver was subjected (Fig. 6a) and on the roller frame to measure vibration due to roller motion (Fig. 6b). Vibration data from the accelerometers were recorded to a computer using special software with a custom made 'on board' data acquisition system mounted on the tool bar (Fig. 6c).

The day before rolling/crimping, rye height and biomass were determined from each plot. The height was measured at ten different randomly chosen locations throughout the plot using a custom-made scale rod and then averaged. The biomass was collected from three different locations of each plot using a 0.25 m^2 area (0.5 m × 0.5 m square) frame. The collected rye biomass was oven dried for 72 h at 55°C using an electric oven (Model No. SC-350 from Grieve Corporation, Round Lake, Illinois). Rye termination, based on visual desiccation, was estimated on a scale of 0 (no desiccation) to 100 (complete desiccation all plants)[15], and was evaluated on a weekly basis at 1, 2 and 3 weeks after rolling.

Table 1. Rye mortality (%) for roller types and operating speeds. The same letters indicate no significant differences within each column.

Roller type	Speed ($km\,h^{-1}$)	2006			2007			2008		
		1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks
No roller	N/A	75 d	96 c	99 b	56 e	75 d	91 c	40 d	60 d	85 b
Straight bar	3.2	90 bc	99 ab	99 b	74 bc	92 bc	98 b	81 bc	95 b	99 a
	6.4	90 bc	99 ab	99 b	74 bc	94 b	97 b	82 b	94 bc	98 a
Curved bar	3.2	90 bc	99 ab	99 b	75 bc	93 bc	98 ab	82 b	93 bc	99 a
	6.4	90 bc	98 b	99 b	73 bcd	91 bc	98 ab	81 bc	95 b	98 a
Smooth w/original cam	3.2	90 bc	99 ab	99 b	71 cd	91 bc	97 b	80 bc	93 bc	99 a
	6.4	90 bc	99 ab	99 b	74 bc	93 bc	97 b	80 bc	93 bc	98 a
Smooth w/modified cam	3.2	90 bc	99 ab	99 b	73 bcd	92 bc	97 b	81 bc	94 bc	99 a
	6.4	89 c	98 b	99 b	72 bcd	91 bc	98 ab	79 c	93 bc	99 a
Smooth drum	3.2	90 bc	98 b	99 b	69 d	90 c	97 b	80 bc	93 bc	98 a
	6.4	90 bc	99 ab	99 b	71 cd	92 bc	97 b	80 bc	92 c	98 a
Smooth drum w/glyphosate	3.2	98 a	100 a	100 a	96 a	100 a	100 a	98 a	98 a	100 a
	6.4	98 a	100 a	100 a	96 a	100 a	100 a	97 a	99 a	100 a
Two-stage roller	3.2	90 bc	98 b	99 b	76 b	94 b	97 b	80 bc	93 bc	98 a
	6.4	93 ab	99 ab	99 b	71 cd	91 bc	97 b	82 b	94 bc	98 a
LSD at $a = 0.1$		5.2	1.3	0.3	4.8	3.3	2.1	2.0	2.2	1.1

Percentages of rye mortality were transformed using an arcsine square-root transformation method[16], but this transformation did not result in a change in the analysis of variance (ANOVA). Thus, non-transformed means are presented. Rolling treatments were considered fixed effects and years were considered random effects. For vibration analysis, original vibration data were used. All acceleration data are reported in RMS values. ANOVA was performed on rye biomass, height, termination rates, VMC and vibrations, using SAS[17]. Treatment means were separated by the Fisher's protected LSD test at the 0.10 probability level. Where interactions between treatments and years occurred, data were presented separately and where no interactions were present, data were combined.

Results

Rye height and biomass

Interactions between years and roller treatments were not detected for biomass production and plant height of the rye cover crop (data not presented). Rye plant height was similar across all 3 years and averaged 167 cm. In contrast, biomass production before rolling was greater at $7688\,kg\,ha^{-1}$ in 2006, and $7811\,kg\,ha^{-1}$ in 2007, than in 2008 when production totaled $6800\,kg\,ha^{-1}$ ($P < 0.01$).

Rye termination

Interactions between years and rolling treatments were detected for rye termination rates ($P < 0.0001$), so years were analyzed separately. In 2006, 1 week after rolling, highest rye mortality (98%) resulted when the smooth drum plus glyphosate was used at either speed (Table 1). Between 89 and 93% mortality resulted when the smooth drum and other roller types were used without herbicide. For non-rolled rye, the mortality rate was 75%. Two weeks after rolling, rye termination was 100% for the smooth drum plus glyphosate at both speeds, and at least 98% for the other roller treatments. Mortality for non-rolled rye was 96%. Three weeks after rolling, all rolling treatments resulted in at least 99% rye mortality.

In 2007, 1 week after rolling, highest mortality (96%) was reported for the smooth drum with glyphosate at both speeds (Table 1). A lower mortality (69%) was reported for the smooth drum by itself at both speeds. The two-stage roller at $3.2\,km\,h^{-1}$ and the straight bar roller at both speeds resulted in 76 and 74% mortality, respectively. Other roller types at both speeds caused rye mortality ranging from 71 to 74%. For the non-rolled rye control, mortality was 56%. Two weeks after rolling, 100% mortality was reported for the smooth drum plus glyphosate, and from 90 to 94% for roller treatments without herbicide. Mortality of non-rolled rye was 75%. Rye mortality was at least 97% 3 weeks after rolling.

In 2008, 1 week after rolling, mortality for the smooth drum with glyphosate was 98% at $3.2\,km\,h^{-1}$ and 97% at $6.4\,km\,h^{-1}$ (Table 1). Other roller treatments resulted in mortality rates between 79 and 82%. For non-rolled rye, the mortality rate was 40%. Two weeks after rolling, a 99% mortality rate was reported for the smooth drum plus glyphosate at $6.4\,km\,h^{-1}$, and 98% at $3\,km\,h^{-1}$. For rollers without herbicide, the mortality rate was between 92 and 95%. The mortality rate for the non-rolled rye treatment was 60%. The mortality rate was at least 98% 3 weeks after rye was rolled.

It should be noted that rye mortality was at least 90% by 2 weeks after roller treatments were imposed in each year of this study. Previous research[1] suggests that this mortality rate was high enough for successful establishment of a cash crop into the rye residue. Our results suggest that cash crop

Table 2. Volumetric soil moisture content averaged over operating speeds (%) for roller types. Same letters indicate no significant differences within each column.

Roller type	2006				2007				2008			
	Day of rolling	1 week after rolling	2 weeks after rolling	3 weeks after rolling	Day of rolling	1 week after rolling	2 weeks after rolling	3 weeks after rolling	Day of rolling	1 week after rolling	2 weeks after rolling	3 weeks after rolling
No roller	6.2 d	4.8 c	2.5 d	15.0 d	6.2 b	1.1 d	0.0 c	0.0 c	6.9 b	2.3 b	2.7 c	4.4 c
Straight bar	7.0 cd	8.6 ab	7.0 ab	17.9 abc	8.6 a	3.7 ab	1.8 ab	0.5 ab	7.7 a	5.8 a	5.5 ab	8.1 b
Curved bar	8.2 a	8.9 ab	6.6 abc	18.5 abc	8.4 a	3.7 ab	1.4 b	0.4 ab	7.6 a	5.4 a	5.7 ab	7.7 b
Smooth original cam	7.1 cd	7.8 b	5.7 c	17.0 c	8.4 a	3.5 bc	1.4 b	0.2 bc	7.7 a	5.6 a	5.2 b	7.4 b
Smooth modified cam	7.2 cd	8.6 ab	6.3 abc	17.5 bc	8.3 a	3.4 bc	1.9 ab	0.3 b	8.2 a	6.1 a	5.9 a	8.1 b
Smooth drum	7.5 abc	8.4 ab	6.1 bc	17.5 bc	8.1 a	3.4 bc	1.4 b	0.4 ab	8.1 a	5.9 a	5.5 ab	7.6 b
Smooth drum w/glyphosate	8.1 ab	9.2 a	6.9 ab	19.3 a	8.6 a	4.0 a	2.0 a	0.7 a	8.1 a	5.8 a	6.0 a	9.2 a
Two stage	7.6 abc	8.6 ab	7.2 a	18.7 ab	8.1 a	3.4 bc	1.4 b	0.3 b	8.0 a	5.8 a	5.8 ab	8.0 b
LSD $a = 0.1$	0.99	1.14	0.98	1.58	0.50	3.30	0.50	0.31	0.63	0.68	0.70	0.86

seeding can proceed within 14 days of terminating a rye cover crop using the roller types evaluated in this study and under similar environmental conditions.

Volumetric soil moisture content

Interactions between years and treatments for VMC were detected ($P = 0.03$), so years were analyzed separately. No significant differences in VMC occurred between operating speeds in any year on the four sampling dates, so VMC is reported for each roller type as an average across both operating speeds (Table 2). Volumetric soil moisture content varied from 6.2% for non-rolled rye to 8.2% for the curved bars roller on the day of the rolling operation in 2006. Even though VMC was measured on the same day after the rolling treatments were applied, there was a 6-h delay between when treatments were applied and when VMC was determined. The lower VMC for non-rolled rye might be associated with higher water evapotranspiration of living plants and a partially exposed bare soil surface compared with rolled rye, which created a residue mat (mulch) that provided complete soil protection after rolling and better conservation of soil moisture. Additionally, the mat formed by the rolled residue seemed to protect the soil from crusting and evaporation, and restrict weed emergence. Also, there probably was limited, if any, water and nutrient uptake by rolled plants, since stems were injured by the crimping action of the rollers.

One week after rolling, VMC ranged from 7.8% for the smooth drum with the original cam to 9.2% for the smooth drum plus glyphosate (Table 2). Differences in VMC were not detected between other roller treatments. VMC was 4.8% and lower in non-rolled than rolled rye plots. Two weeks after rolling, VMC ranged from 5.7% for the smooth roller with the original cam to 7.2% for the two-stage roller. For non-rolled rye, soil moisture decreased to 2.5%, suggesting that rolled rye residue provided an effective surface cover. Three weeks after rolling, increased VMC (from 15 to 19.3%) across treatments was associated with a rainfall event prior to data collection.

In spring of 2007, a drought occurred in Alabama causing a severe soil moisture deficit, and in some locations complete soil–water depletion. The day of rolling operations, all rolled rye treatments kept VMC between 8.1 and 8.6%, whereas VMC for standing rye was significantly lower (6.2%) (Table 2). One week after rolling, the VMC for rolled rye residue measured between 3.4 and 4%, while for standing rye the VMC dropped to 1.1%. At 2 weeks after rolling, VMC was between 1.4 and 2% in rolled rye plots, and less than 1% (from 0.2 to 0.7%) at 3 weeks after rolling. During the drought period in 2007, at 2 weeks after rolling and beyond, VMC for non-rolled standing rye consistently measured 0%.

In 2008, VMC for standing rye on the day of rolling was 6.9% and was significantly lower compared with all rolled rye treatments, which ranged from 7.7 to 8.2%. No significant difference in VMC was found between the rolled

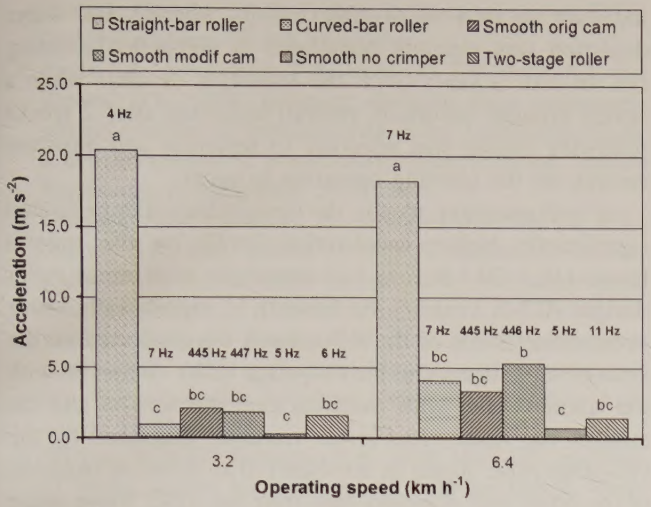

Figure 7. Vertical acceleration level (RMS) measured on the roller frame for different roller types and operating speeds. Different letters indicate differences between treatments within and across operating speeds. The same letters represent no significant differences between treatments, LSD = 4.2 at $a = 0.1$ of significance level.

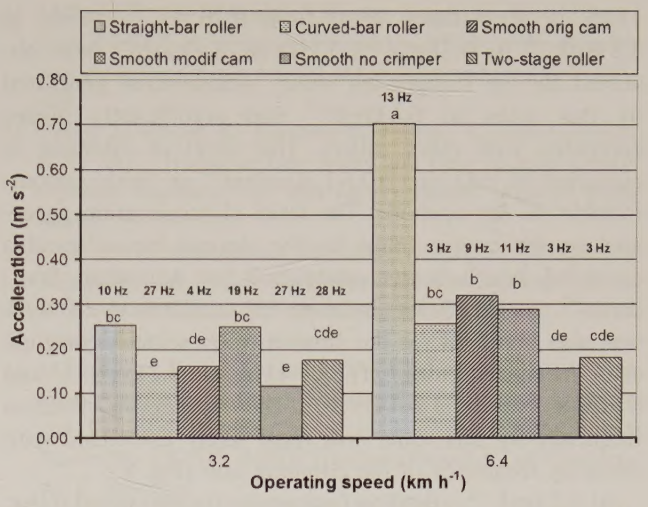

Figure 8. Vertical acceleration level (RMS) measured on the tractor frame for each roller type and operating speed. Different letters indicate differences between treatments within and across operating speeds. The same letters indicate no significant difference between treatments, LSD = 0.085 at $a = 0.1$ of significance level.

treatments. One week after rolling, VMC was 2.3% for non-rolled standing rye compared with 5.4 and 6.1% for rolled rye, depending on the treatment. Similar to VMC measured at the day of treatment application, no significant difference in VMC was found between the roller treatments. Two weeks after rolling, the VMC was similar to that measured 1 week after rolling; VMC measured 2.7% for non-rolled rye and between 5.2 and 6.0% for rolled rye treatments. Three weeks after rolling, VMC ranged from 4.4% for standing rye to 9.2% for the smooth roller plus glyphosate treatment. The increase in VMC was associated with rainfall, which occurred after the second and before the third week after rolling. Data from 3 years were consistent and suggested that rolled residue protected the soil from moisture loss by creating a mulch effect. During the severe drought in 2007, the rolled rye residue cover provided effective surface mulch that limited evaporation for up to 1 week after rye termination.

Vibration

Roller frame vibration. At both operating speeds, the straight bar roller generated significantly higher acceleration levels on the roller frame (18.2–20.3 $m\,s^{-2}$) in comparison with the other roller designs (0.2–5.3 $m\,s^{-2}$). Vibration generated by the straight bar roller was approximately ten times higher at 3.2 $km\,h^{-1}$ and four times higher at 6.4 $km\,h^{-1}$ in comparison with other roller designs. With increased operating speed, acceleration level on the roller frame did not increase significantly for all roller designs, although numerical values of acceleration were higher at 6.4 $km\,h^{-1}$ than at 3.2 $km\,h^{-1}$ (Fig. 7). With increased operating speed, there was no significant difference in acceleration level on the straight bar roller frame (20.3 $m\,s^{-2}$, 3.5 Hz at 3.2 $km\,h^{-1}$; and 18.2 $m\,s^{-2}$, 7 Hz at 6.4 $km\,h^{-1}$). The doubling in vibration frequency for the straight bar roller was most likely associated with the increased crimping frequency from the higher operating speed.

Vibration frequency for the two-stage roller increased with increasing operating speed (i.e., 1.4 $m\,s^{-2}$, 6 Hz at 3.2 $km\,h^{-1}$, and 1.2 $m\,s^{-2}$, 11 Hz at 6.4 $km\,h^{-1}$), indicating an increase in crimping frequency for the two-stage roller. Vibration frequencies for the curved roller (7 Hz at both speeds) and for the smooth roller drum without crimper (5 Hz at both speeds) indicate an absence of vibratory crimping motion resulting in smoother operation. The smooth roller with the original and modified cam mechanisms exhibited very high vibration frequencies from 445 to 447 Hz. These high frequencies might be associated with the natural frequency of the crimping arm assembly from crimping against a non-uniform soil surface.

Newer roller designs generated substantially less vibration on the roller frame compared with the original straight bar. At 6.4 $km\,h^{-1}$, the lowest acceleration level on roller frame was reported for the smooth roller drum and the two-stage roller, although no significant differences in acceleration were found between these two rollers, the curved roller and the smooth roller with the original cam mechanism.

Tractor frame vibration. When comparing the original straight bar roller design with the other roller designs, there was a significant difference in acceleration level averaged over operating speed between straight bar roller and other roller types ($P < 0.01$). With increased operating speed, the acceleration level measured on the tractor frame also increased. There was a significant difference in average acceleration level generated on the tractor frame of 0.17 $m\,s^{-2}$ at 3.2 $km\,h^{-1}$ and 0.30 $m\,s^{-2}$ at 6.4 $km\,h^{-1}$ ($P < 0.01$). Specifically, the highest increase of

173% in acceleration level from 0.26 m s^{-2}, 10 Hz, at 3.2 km h^{-1} to 0.71 m s^{-2}, 13 Hz at 6.4 km h^{-1} was observed for the straight bar roller. Acceleration generated by this roller at 6.4 km h^{-1} was significantly higher compared with other rollers. This level of vibration is classified by ISO No. 2631-1 standard[13] as 'fairly uncomfortable' to the operator. The level of acceleration generated on the tractor frame by the straight bar roller also exceeded health limits established by Australian Standards[14]. A significant increase in acceleration of 99% was also observed for the smooth roller with the original cam mechanism 0.17 m s^{-2}, 4 Hz at 3.2 km h^{-1} and 0.32 m s^{-2}, 9 Hz at 6.4 km h^{-1}. The doubling in vibration frequency by this roller was most likely associated with crimping frequency of the crimping arm (Fig. 8).

At 3.2 km h^{-1}, vibration frequencies for the curved roller, the smooth roller drum and for the two-stage roller ranged from 27 to 28 Hz. Because acceleration levels measured on the tractor frame with these rollers were low (0.14–0.17 m s^{-2}), the recorded frequencies could be associated with the engine vibration frequency at 1700 rpm (28.8 Hz) rather than with roller vibrations. In contrast, vibration frequencies for these three rollers at 6.4 km h^{-1} were lower (3 Hz) and most likely were associated with roller vibrations that were transferred to the tractor frame. The lowest acceleration levels on the tractor frame at 6.4 km h^{-1} were generated by the smooth drum (0.16 m s^{-2}, 3 Hz) and the two-stage roller (0.18 m s^{-2}, 3 Hz). No significant difference in acceleration level due to increased speed was found for the smooth roller drum without crimper, smooth roller with modified cam mechanism and the two-stage roller. Overall (except for the straight bar roller), the new roller designs generated from 0.12 to 0.32 m s^{-2} on the tractor frame (classified by ISO[13] as a 'little or not uncomfortable'). These acceleration levels were also below health limits established by Australian standards[14].

Summary and Conclusion

All tested roller designs resulted in at least 98% mortality of rye plants 2 weeks after rolling in 2006, 90% in 2007 and 92% in 2008. A relatively minor but sometimes statistically significant increase in rye mortality resulted when roller use was combined with the application of glyphosate and termination was evaluated 2 weeks after rolling. By comparison, mortality of non-rolled standing rye was 96% in 2006, but only 75% in 2007 and 60% in 2008. The speed at which rolling occurred did not affect the rye mortality rate. These results indicate that a rye cover crop can be terminated effectively within 14 days when rolling is delayed until the early kernel formation stage of reproductive growth.

Increasing the rolling operating speed did not affect VMC. Generally, rolled rye provided better protection in preserving soil moisture compared with non-rolled standing rye. In 2007, when a severe drought condition occurred, rolled rye residue effectively protected soil from losing moisture up to 1 week after rolling, whereas soil water depletion was virtually completed in non-rolled standing rye. In 2 of 3 years (with the exception of 2007 when a severe drought occurred), rainfall occurring after 2 weeks following rolling was adequate to replenish soil moisture enough for the planting operation to occur.

At both operating speeds, the straight bar roller generated significantly higher acceleration levels on the roller's frame (18.2–20.3 m s^{-2}) in comparison with other roller designs (0.2–5.3 m s^{-2}). At 6.4 km h^{-1}, significantly lower acceleration levels on the roller frame were reported for the smooth roller drum and the two-stage roller compared with the smooth roller with modified cam mechanism and the straight bar roller. The lower vibration generated by the two-stage roller might be attributed to an effective isolation of the drum with crimping bars from the roller frame using rubber isolators.

With increased operating speed, the highest acceleration increase on the tractor frame was recorded with the straight bar original design, compared with newer roller designs. At 6.4 km h^{-1}, acceleration level (0.7 m s^{-2}) generated by the straight bar roller was classified as 'fairly uncomfortable' by ISO standards for vibration exposure and exceeded the health limit based on Australian standards. At both speeds, acceleration levels for newer roller designs were below comfort and health limits established by International standards.

Overall, all roller designs effectively terminated rye. Speed did not affect mortality and VMC, but did increase vibration levels on the tractor frame. Compared with the original straight-bar roller, the new roller crimper concepts (especially the curved and the two-stage roller) significantly reduced vibration both on the tractor's and roller's frames, while maintaining or exceeding mortality provided by the original straight bar roller design. Additional research is needed to determine the effectiveness of different roller designs in terminating cereal cover crops at their different (earlier) growth stages to select the best roller design.

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Pesticide distribution and use in vegetable production in the Red River Delta of Vietnam

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Abstract

For a long time pesticides attracted interest from the Vietnamese governments and farmers for their positive effects in protecting crop yield losses resulting from pests and other plant diseases. Recently, the negative effects of pesticides on human health, natural food chains and the environment are increasingly being taken into account by both state and non-state actors. Striking a balance between positive and negative effects is complicated as, most likely, pesticides will continue to maintain their vital role in an agriculture-based country such as Vietnam. However, recently a shift can be noticed in farmers' selection and application of pesticides, initiated mainly by farmers themselves and to a lesser extent also by other actors such as the government, pesticide companies and distributors. This article provides an empirical insight into this shift, based on the results from research in four provinces in the Red River Delta. Possible implications for policies toward greening pesticide handling practices in vegetable production are drawn, such as removing inexpensive pesticides (often associated with high toxicity) from the market, giving technical training on pesticide selection and use to farmers, and reconsidering the role different actors can play in future safe vegetable production programs.

Key words: pesticide distribution, pesticide use, toxicity, environment, agriculture, Red River Delta

Developments in pesticide use in agriculture

Vietnam is a country with a long history of agricultural production. This sector has been and will remain a major motor for the national economy as well as for the livelihood and well-being of a major part of its population. Since Vietnam adopted a policy promoting a market economy in the mid-1980s, agricultural production has become more diversified whereby the area used for growing vegetables has increased remarkably, i.e., from 328,200 hectares (ha) in 1995 to 452,900 ha in 2000 and 525,900 ha in 2005[1]. The Ministry of Agriculture and Rural Development has even planned to expand this area to 800,000 ha by 2010[2]. This expansion of the area destined for vegetable growing in Vietnam, goes together with a remarkable increase of the total quantity of pesticides used for this activity, leading to several health and environmental problems. This section will explore this history to provide a background for the empirical study on the changes in pesticide use in Vietnam.

The initial promotion of the use of pesticides by the Vietnamese government was greatly facilitated by the centralized management and collectivized production, which dominated economic policies between 1959 and the early 1980s[3]. By 1988, following Vietnam's *Doi Moi* (or Renovation) policy toward a market orientation, the distribution of agricultural inputs was removed from the control of cooperatives[4]—the prevailing unit for agricultural production promoted by the Vietnamese government during the collectivization production period, i.e., from the end of the 1950s until the beginning of the 1980s—and given into the hands of private entrepreneurs who got engaged in the import, formulation and distribution of pesticides for agricultural crops. In less than 40 years, the initial pesticide use of just 100 tons per year in the 1950s[5] had multiplied 150 times by 1991[6]. Particularly as a result of the privatization of agricultural production in Vietnam, pesticides were applied even more intensively, and their use therefore grew rapidly from 15,000 tons in 1991 to 35,000 tons in 2002[6]. The expenditures for pesticide imports increased 13.5 times between 1991 and 2006[6,7]. These rapid changes not only concerned the quantities, but also the types of pesticides used. The numbers of both active ingredients and pesticide formulations/re-branded products distributed and used in

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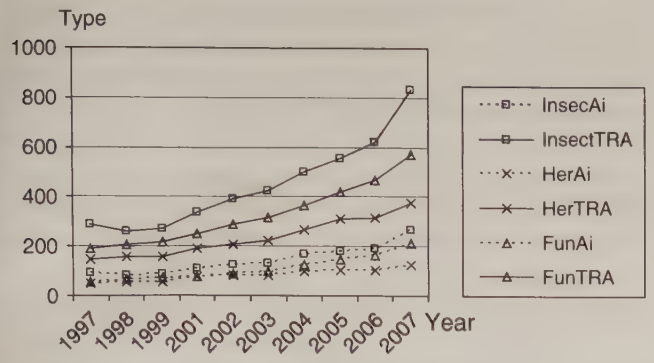

Figure 1. Types of pesticides (in Ai and formulation) distributed in Vietnam (1997–2007). Note: Ai, active ingredient; InsecAi, insecticide Ai; InsectTRA, insecticide trading names; HerAi, herbicide Ai; HerTRA, herbicide trading names; FunAi, fungicide Ai; FunTRA, fungicide trading names. Source: Ministry of Agriculture and Rural Development (1997–2007).

Vietnam increased remarkably, especially during the past decade. On average, 38 new types of pesticides were registered annually in the years between 1997 and 2001, and 149 during the period from 2002 to 2007[8–17] (Fig. 1).

Currently, pesticide use per hectare is higher in the production of vegetables. In one of the major agricultural areas—the Red River Delta—the average amount of pesticides used is 5.52 kg ha^{-1} cropping season^{-1} for vegetables compared with 3.34 kg ha^{-1} for rice, 0.88 kg ha^{-1} for other food crops (e.g., maize and sweet potato), 3.34 kg ha^{-1} for short-season industrial crops (e.g., soybean and peanut) and 3.08 kg ha^{-1} for long-season industrial crops (e.g., tea and coffee). These figures are comparable with other ecological regions of Vietnam[5].

The increased use of pesticides has positive effects such as higher cropping yields and, to a certain extent, improved quality of the products. However, pesticides also have negative health effects for the actors directly or indirectly involved in the food supply chain (such as farmers, traders and consumers) especially when pesticides are improperly applied. Poor farmer knowledge on the content, use and risks of these chemicals, ineffective governmental enforcement of pesticides' regulations[5,18], and strong profit-driven interests among pesticide traders and users, have led to an increased use of cheap and rather hazardous pesticides in Vietnam in the 1990s[5,19]. In this situation, the Vietnamese population has been threatened by the health risks associated with direct and indirect exposure to pesticides. For instance, in 2002 more than 7000 cases of food poisoning from pesticide residues (involving 7647 people) were reported, causing 277 deaths in 37 of the 61 provinces[20]. These numbers of acute poisoning from direct and indirect exposure to pesticides do not include the numerous cases of 'silent' casualties by pesticides[21,22].

Given these problems, agricultural authorities at ministerial, provincial and district levels have recently invested much to redirect vegetable farming practices to become less pesticide-based. Many training courses on technical knowledge, integrated pest management and the proper use of pesticides have been organized for farmers. In addition, field demonstrations and zone-planning for the so-called 'safe vegetable production' (the production follows a set of procedures regarding good soil and water condition, use of less toxic chemical inputs, clean seed/seedlings and adoption of integrated pest management strategy) have been implemented, especially in the peri-urban areas of Hanoi and in Hai Duong and Hung Yen provinces. However, it is not clear whether these interventions by the agricultural authorities have resulted in improvements in distribution and use of pesticides, as extensive and reliable information on pesticide trading and on farmers' practices in using pesticides is lacking.

Against this background, this empirical study focuses on two main objectives. First, as so little is known about the developments in pesticide distribution and use in Vietnam, our first objective was to assess the recent changes in this field, emphasizing the Red River Delta. Our second objective was to explain how these changes are taking place, focusing on the state actors and non-state actors involved in the distribution and application of pesticides. This research will provide a more thorough understanding of the decisions farmers make in selecting and using pesticides. After introducing the research methodology, a detailed analysis of the pesticide distribution practices is presented. This is followed by an analysis of the factors that influence pesticide selection and use by farmers. The final section formulates conclusions and recommendations for a more environmentally friendly use of pesticides.

Methodology

This article is based on two field studies in the Red River Delta in northern Vietnam, supplemented with a considerable number of interviews with stakeholders and informants.

A first empirical study was done on the distribution and use of pesticides and carried out in two provinces in the Red River Delta: Hanoi and Hai Duong (Fig. 2). These provinces were selected because they produce large quantities of vegetables for markets in different provinces and regions throughout Vietnam. In Hanoi, the major vegetables were cauliflowers, choysum, kolhrabi, wax gourd, wrapped heart mustard, headed cabbage and carrot. These vegetables are mostly grown in winter and early spring. In summer, farmers grow rice and maize as major crops and some vegetables such as choysum, wax gourd, wrapped heart mustard and bitter melon. By contrast, in Hai Duong, the types of vegetables grown are less diverse. The major vegetables are headed cabbage, wrapped heart mustard, cucumber and kolhrabi. These are mainly grown in winter. In summer, farmers often grow water melon, rice and maize with a small area for headed cabbage, wrapped heart mustard and cucumber. Major insects and diseases on vegetables are: flea beetle, imported cabbage webworm,

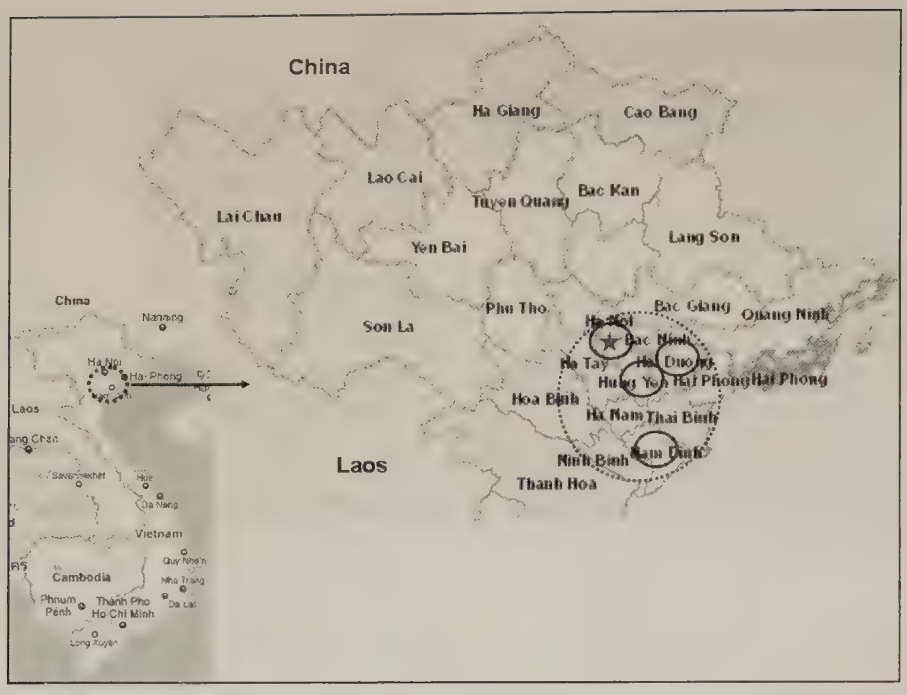

Figure 2. Locations of the study site in northern Vietnam (Hanoi, Hai Duong, Hung Yen and Nam Dinh province).

diamond back moth, cotton bollworm, white fly, aphid, black cutworm, *Rhizoctonia*, *Xanthomonas* and *Alternaria*. In addition, the organization of vegetable production varies between these provinces, from more intensive in Hanoi to less intensive in Hai Duong province. As such, these areas are representative of the existing variation in Red River Delta.

For the first empirical study, a farmers' survey was conducted from September to November 2006. In each province, two communities—one in which the state had targeted for 'safe vegetable production' and another without such policy which therefore can be called 'normal vegetable production'—were selected. In each community between 30 and 33 farmers were systematically randomly selected, resulting in a total survey of 125 farmers. These 125 farmers were interviewed with the help of structured questionnaires to understand their agricultural practices and socio-economic conditions, i.e., land availability, labor availability, level of education, their present and past (5–7 years ago) vegetable farming activities. These background data were supplemented with questions on related issues such as the insect pests and diseases they encounter, their access to pesticides, to technical know-how and to the vegetable market, with a focus on the pesticide selection and use and on the actors and factors that influence their decision-making. Because farmers do not record or remember the exact names of the pesticides they have used, the research team borrowed all types of pesticides available in the large retailing shops in the area as samples for the interviewees. Each researcher brought a sample of about 40 types of pesticides and each farmer was requested to select the five pesticides they most regularly and recently applied. These five pesticides were then used to guide follow-up questions on toxic classification, pesticide cocktailing practices and pre-harvest interval.

Parallel with this survey, an additional number of 32 farmers in Dong Anh district, Hanoi, were monitored on a daily basis between August 2006 and March 2007 for all their farming activities. Similar monitoring data had been gathered before from these 32 farm households between August 2002 and March 2003 in the VEGSYS Project (Sustainable Technologies for Pest and Disease Management and Soil Fertility Management in Smallholder Vegetable Production in Sichuan, China and Red River Delta, Vietnam, http://www.vegsys.nl). This repetition allows a longitudinal comparison to track changes over time. The monitoring from August 2002 to March 2003 and from August 2006 to March 2007 will be termed monitoring periods 1 and 2, respectively (hereafter MP1 and MP2). A total of 199 primary production units with a sown area of 7.57 ha had been monitored in MP1 and 225 primary production units with a sown area of 8.16 ha in MP2 (a primary production unit is a full cycle of a certain crop grown on a specific plot).

Data originating from the farmers' survey are mostly reported based on the percentage of farmers' responses. In addition, by using SPSS software, several observed variables have been analyzed to determine factors that explain farmers' decision-making regarding pesticide selection and use. Discriminant analysis of the observed variables is also used to determine differences between the two groups of farmers (i.e., safe vegetable and normal vegetable production) and the two provinces. Quantitative data from farm monitoring are presented by average pesticide application

(means) and statistically analyzed with Independent-Samples T Test to determine whether there is any change in pesticide application practices between MP1 and MP2.

Finally, this article also includes information gathered through semi-structured interviews with five staff members from agricultural departments, eight officials from plant protection departments, two researchers, six pesticide retailers and staff from pesticide companies. These interviews were supplemented with additional open interviews with 13 farmers in two other provinces—Hung Yen and Nam Dinh provinces (cf. Fig. 2)—to supplement those in Hanoi and Hai Duong provinces with a focus on recent changes in practices of pesticide distribution and application on vegetables as well as on the drivers for those changes.

Pesticide distribution: beyond short-term profits?

Since the introduction of the *Doi Moi* policy in the 1980s, the involvement of private actors in different sectors of the Vietnamese economy increased, including in the import, formulation and distribution of pesticides. Though government documents contain strict regulations for these activities, weak enforcement by the state has resulted in disorderly practices in marketing and handling pesticides. Recently however, as we will argue in this section, increased competition between pesticide companies and retailers, and a growing awareness among farmers of their potential negative effects, have resulted in some signs of improvement in pesticide practices (including the import, formulation and distribution) in Vietnam.

At present, the pesticide distribution system in the country is in the hands of a large number of small-scale private businesses. The number of companies involved in formulation and distribution of pesticides increased from 137 in 1999 to 193 in 2006[10,16]. Parallel with this trend, the number of pesticide retailers increased even faster. The number of retailers (excluding part-timers who often do not register their business) was estimated at around 19,000 in 2001[23], which grew significantly over the following years. For instance, the number of retailers inspected by Plant Protection Department officials in 2002 already totaled 27,578[18], while a number of retailers still remained uninspected. Since Vietnamese data are often not very reliable; these data would mean an increase of over 40% in 1 year[24].

This rapid growth in the number of pesticide companies and retailers is an indication for the fact that the pesticide market in Vietnam is highly lucrative and 'parasitic'. 'Parasitic' pesticide, in this sense, refers to cheap pesticides often with low effectiveness produced and/or packaged by small-scale Vietnamese pesticide companies. It is often applied in a cocktail with other pesticides, mostly of better quality, rather than used separately. Farmers were pushed to apply certain pesticides by retailers on whom they most rely on for guidance on the selection and application of pesticides. The market opportunities were particularly high when the official regulations that define pesticides as a special product for which formulation, trade and use is only allowed under specific conditions such as certificates for technical know-how, business, health, etc., were not (completely) followed[25]. Due to the general inadequacy in governmental enforcement of this policy, there were many companies violating the existing regulations. For instance, a comprehensive nation-wide inspection conducted by the Plant Protection Department in 2000[26] found that out of the 10,233 pesticide retailers controlled, 5132 (50.2%) had no adequate storage facility for pesticides and that many stores failed to follow the safety guidelines. Pesticides were repeatedly stored near human foods and animal feed. Moreover, this Plant Protection Department inspection reported that 2388 retailers (23.4%) had no official permission to perform their business and as many as 8868 retailers (86.7%) had no certificate on technical pesticide knowledge[26]. In 2002, the inspection of 27,578 pesticide retailers detected 5183 (18.8%) breaking the regulations. The number of retailers violating the official regulations even increased to 19.9% in 2003, according to the inspection[18]. On another occasion during the same period, out of 36 pesticide companies inspected, 10 were violating the regulations[18].

Simultaneously, there was substantial trade in illegal pesticides (mainly of highly toxic products). The nation-wide inspection in 2000 detected 2500 kg of banned pesticides and 4753 liters and 5645 kg of illegally imported pesticides[26]. In 2001, government officials confiscated 7959.5 kg of illegal pesticides when inspecting pesticide retailers[23]. However, as the inspection only applies visual and easy-to-check indicators regarding retailing and trading practices in pesticides, more 'sophisticated' violations are often not detected. So inspectors verify the presence of formal certificates on technical know-how for pesticide companies, of storage facilities for retailers, of information about the origin and expiry dates of the pesticides and of information labels on the packaged pesticides, but they cannot control the chemical composition of the inert ingredients that are used as carriers or bulk agents for the pesticides. Sometimes these inert ingredients are as toxic as, or even more toxic than, the active ingredients (Ai)[27]. Also, the compatibility between the real percentage of Ai(s), the real types of Ai(s) and the information on Ai(s) that is mentioned on the labels cannot be checked. For instance, our respondents from the pesticide companies, retailers and even many farmers suspect that some types of pesticides registered as from biological origin could in reality be from chemical sources, because they have a quick impact and high efficacy. Another strategy regularly applied by pesticide companies that evade regulations, which is greatly facilitated by the limited time available for inspection by the official teams, is to use different information labels for large packages (intended for official inspection) and for small packages (intended for farmers).

Our field research discovered several examples of such label discrepancies in a pesticide shop in Gia Lam, Hanoi: the pre-harvest interval for the pesticide Reasgant 1.8EC (Abamectin) was 7 days according to the information on the large packages, but the label on the small packages mentioned only 3 days, which makes this product more attractive for farmers. Similarly, the pre-harvest interval for the pesticide Pounce 50EC (Permethrin) recommended on the large package was 12 days, while on the small package only 7 days was mentioned. Other pesticides such as PhiRonin 50SC (Fipronil) did not even have any pre-harvest interval information on the small packages at all, though on the large packages 14 days (for rice and beans) was indicated. We also found that several companies renewed the expiry date for already expired pesticides or even engaged in the production of counterfeit pesticides.

Given the competition between pesticide companies, introducing new products on the market is a key strategy to maintain (or expand) market share and profit. Foreign pesticide companies, such as Syngenta, Monsanto and Bayer, seem to adopt a bottom-up approach in introducing and promoting their products. When they put a new product on the market, they often start with an extensive and intensive promotion program and offer the product to farmers for free, before really engaging in trading it commercially. By contrast, domestic Vietnamese companies generally adopt a top-down, often parasitic, approach. The main reason for this difference is that unofficial open-door pesticide policy from the Vietnamese Ministry of Agriculture and Rural Development prevents companies from gaining a monopoly on a particular product for a certain period of time. Apart from this, the rapid emergence of resistance against pesticides among crops is shortening the period of effectiveness for many [formulated] pesticides with old Ais (mainly originating from China). For these reasons, once a local Vietnamese company decides to market a new product, it will do this as quickly as possible to take advantage of the temporary opportunities, for which an extensive retailer network is essential. Vietnamese companies do not have enough financial resources to invest in a prior extensive and intensive promotion program like foreign companies. Pesticide companies rely on retailers to sell their products as farmers are heavily dependent on them for the selection of pesticides and information about their use. Thus introducing 'new' products on the market is a combined strategy for companies and retailers to maintain (or improve) their market position. Although, such 'new' products often do not really have a new composition, their successful introduction offers large benefits for both the company and the retailer because farmers are not yet familiar with the product and have no idea about its real price. Developing and registering 'new' products is also a strategy in the competition between wholesalers and retailers operating on the same location. As the same product may be registered under different trading names, each wholesaler and his retailing network will have access to one or only a limited number of these trading names. By adopting the strategy of offering special commission fees for their retailers, many smaller Vietnamese pesticide companies have been able to successfully expand their business, illustrated by the growing number of pesticide products registered by Vietnamese companies in recent years[11–16]. The weak and ineffective government enforcement of regulations regarding pesticide formulation, distribution and use, allows many small-scale Vietnamese pesticide companies to put cheap and poorly effective products on the pesticide menu of farmers. Retailers and farmers are aware that if these cheap pesticides are used separately they will have only a limited effect in controlling pests and diseases and, consequently, they are combining them more and more into solutions known as 'cocktails.'

In Vietnam, no formal collaboration exists between pesticide companies, although some negotiations have been ongoing between the large-scale pesticide companies to establish an association to fight counterfeit pesticides and unfair competition, but this has not yet generated a concrete result. For many years, competition from small-scale pesticide companies has been modest, as they did not really challenge the market shares and/or profitability of the large-scale companies. After having enjoyed lucrative profits on this easy market for a number of years, however, Vietnamese pesticide companies are currently challenged by more intense competition. They have to find a strategy to secure their longer-term interests and though they still continue selling parasitic pesticides for short-term profits, they have started to look as well for products with greater intrinsic value (i.e., new compounds) for which they face less competition. This comes together with attempts to increase their reputation among retailers and farmers. Respondents from pesticide companies indicated that they now have to take care not only of their short-term profits, the efficacy of a pesticide and its retailing price, but also of the potential resurgence of the pest resulting from repetitive use by farmers of certain of their products, as it could jeopardize their name and reputation.

Similarly, none of the interviewed pesticide retailers has cooperated with other retailers, not even through exchanges of pesticides or information. They are just competing with each other to protect their present business niche, but this has become more challenging in recent years. Since farmers are gaining increased knowledge on pesticides, a retailer who lacks technical know-how will be pushed out of the market if farmers find out he gave them wrong information about the selection and application of a pesticide. In combination with the increasing awareness among retailers of the potentially harmful effects of pesticides, this has meant an end of pesticide sales by many retailers. This has especially occurred in Hanoi, where farmers are increasingly becoming less dependent on retailers for technical know-how and financial services. For instance, the number of year-round pesticide retailers in Dong Anh district reduced from 128 to 28 between 1998 and 2006, while the number of year-round pesticide retailers in Hai Duong fell

Table 1. Changes in the toxicity of pesticides used by Vietnamese farmers in two provinces during two time periods.

Toxic class (by World Health Organization)	Number of farmers (5–7 years ago)			Number of farmers (at the time of the survey)		
	Hanoi	Hai Duong	Percentage (%)	Hanoi	Hai Duong	Percentage (%)
Ia	32	22	19.1	0	0	0.0
Ib	41	30	25.2	1	1	0.4
II	54	24	27.7	115	73	37.2
III	8	2	3.5	4	24	5.5
U	13	22	12.4	82	47	25.5
Unknown (a)	3	7	3.5	38	94	26.1
Unknown (b)	3	21	8.5	3	23	5.1

Unknown (a), pesticides with known Ai but not listed in IPCS[28]; Unknown (b), pesticides with unknown Ai.

from 820 to 750 from 2005 to 2007. Retailers also stop their business because of reducing financial benefits as a consequence of increased competition. A pesticide retailer in Soc Son district, Hanoi revealed that in the 1990s, he could earn 20 to 25 million VND $year^{-1}$ (or roughly US$1300 to 1600) from pesticide retailing, but in 2003 and 2004 he only earned 5–7 million VND $year^{-1}$ (US$300 to 400), because three other retailers started a similar business in the village. He stopped his pesticide retailing activities in 2005. Retailers explain that in order to keep their clients satisfied they nowadays have to sell more expensive pesticides of high efficacy (meaning newer and safer compounds such as Abamectin, Acetamiprid and Indoxacarb).

Several other factors have contributed to the decline in use of illegal pesticides since the year 2000. Farm household income has increased due to off-farm employment and therefore farmers are willing to spend more for better-quality pesticides, especially for those relying on hired labor for pesticide application. Farmers want to control pests with the first application in order to reduce reapplication costs and labor requirements. This new trend discourages retailers from selling cheaper, less effective and less reliable pesticides (often of Chinese origin). Another reason for reduced use of illegal pesticides is enforcement by state authorities. Retailers repeatedly had to wait for several hours to get illegal pesticides from wholesalers, because these pesticides were kept in secret places and were only taken out if wholesalers felt they were not observed by the responsible state officials (for instance at the end of the day). Moreover, once caught with illegal pesticides, retailers may be forced to pay bribes to officials. One retailer in Hung Yen province said that after he was inspected with illegal pesticides, the money he had to bribe officials was a half of the total benefit that he could get from pesticide business in a year. Finally, farmers themselves have contributed to reduced use of illegal pesticides. For instance, our research found that in February 2005, about 7000 m^2 of wrapped heart mustard rotted in a village of Dong Anh district. The farmers attributed the damage to the illegal pesticide and together they wrote a letter to the communal authorities and, in response, the retailer was fined. The retailer still continues his pesticide sales business but with a reduced number of clients and is no longer selling illegal products.

Pesticide use: toward less toxic active ingredients

In this section, we will report on the results of the survey among 125 farmers to gain better insights into their past and actual pesticide use and into the factors explaining changes in their practices. These data are supplemented with the findings from a farm-monitoring study conducted among 32 farmers from August 2006 to March 2007 in Dong Anh district, Hanoi (termed as MP2). The data from this farm monitoring study are compared with the results from a previous study done from August 2002 to March 2003 (termed as MP1).

From the survey, a total of 282 responses were collected from 125 farmers about their use of pesticides 5–7 years ago. Of all pesticides used in that period 19% belonged to the highest toxicity as classified by World Health Organization (class Ia), 25% to class Ib, 28% fell under class II and 16% to class III and U[28] (unlikely to present an acute hazard in normal use). The rest were either not listed by World Health Organization or contained unknown Ais. For current pesticide use, 505 responses were collected and of the pesticides used in this period, less than 1% was categorized under class Ib of toxicity. The rest belonged to the classes II, III, U and unknown. It deserves mentioning here that, according to other institutions, many unknown pesticides (i.e., Acetamiprid, Abamectin and Indoxacarb) contained low acute and chronic toxic material. Pesticides with unknown Ais accounted for 8.5% in farmers' use 5–7 years ago and 5.1% currently (Table 1).

Insecticides are the most used pesticide and they account for 79 and 77% of the total pesticide selected by farmers 5–7 years ago and currently, respectively. The farm monitoring results showed that over time relatively more insecticides are being used, increasing from 48 to 65% of the total quantity of Ai in the pesticides used in MP1 and

Table 2. Quantity and value of pesticides used by farmers in Hanoi during two time periods.

Toxic class (by World Health Organization)	MP1				MP2			
	Frequency of use (%)	Finished form (%)	Ai (%)	Value (%)	Frequency of use (%)	Finished form (%)	Ai (%)	Value (%)
Ib	1.6	2.0	1.6	3.5	0.9	1.1	1.1	1.5
II	27.1	24.6	18.4	30.6	31.8	41.0	40.6	29.0
III	4.7	11.1	8.7	7.5	3.8	3.1	3.7	3.4
U	25.6	32.4	39.9	23.9	22.8	27.6	31.3	19.0
Unknown (a)	31.9	22.3	31.4	26.5	39.6	26.1	23.3	45.8
Unknown (b)	9.1	7.7	–	8.1	1.1	1.2	–	1.3
Total (in value)*	1697.0	84.8	42.5	551.9	2209.0	106.8	43.8	969.9

* Unit for frequency of use is number, finished form and Ai is kg and value is US$.
Unknown (a), pesticides with known Ai but not listed in IPCS[28]; Unknown (b), pesticides with unknown Ai.

MP2, respectively. Herbicide use is also growing, though not at a similar rate; from 4 to 13%. In contrast, the use of fungicides is declining; down from 48 to 22% of the total Ai in pesticides used by farmers when comparing the two monitoring periods.

The results from farm monitoring furthermore confirm the impression that farmers rely more on pesticides from toxic class II and less on those from class U in MP2 as compared with MP1. This can be explained by the reduction in the use of fungicides, which formed the most-often applied pesticide in toxic class U. Better knowledge of farmers on insects and diseases partly explains the reduction of fungicides used in MP2. For instance, in the MP1, farmers often failed to correctly distinguish between the damage caused by mites and thrips and that resulting from fungi and therefore they relied on fungicides to treat pests. Besides, there is also a remarkable change in the types of pesticides used over time. Pesticides of unknown Ai, which accounted for 7.70% of the total pesticide volume of 84.8 kg (in finished form) in MP1, fell to 1.23% of the total volume of 106.8 kg in MP2 (Table 2). It is important to note that according to Table 1, farmers reported a significantly higher use of pesticides with toxic class Ia in the period 5–7 years ago than the findings for MP1 reported in Table 2. This could be explained by the different approaches adopted for data gathering, i.e., more qualitative indications in Table 1 compared with the quantitative findings used for Table 2.

A shift from more toxic to less toxic Ais between MP1 and MP2 was confirmed from pesticide expenditure data. For example, in MP1 the value (cost ha^{-1}) of the ten most used pesticides accounted for roughly 74% of total Ai quantity, but only for 57% of the total value. By contrast, in MP2, these ten pesticides accounted only for 60% of the total Ai quantity used, but 68% of their total value. The increased use of pesticides such as Acetamiprid and Indoxacarb and the reduction of Endosulfan in MP2 indicate a shift toward the application of newer and safer compounds; this also signifies a trend toward the use of more expensive pesticides (Table 3).

This shift toward increasing use of more expensive and safer pesticides was also statistically confirmed. The Independent-Samples T Test analysis did not confirm a significant difference in the quantity of pesticides used per ha (both in finished form and in terms of Ai) between MP1 and MP2 for both farm household- and primary production unit-based analysis. The analysis, however, confirmed the significance of the difference between the pesticides used in MP1 and MP2 in terms of their value ($df = 60$, $P < 0.01$ and $df = 415$, $P < 0.01$ for household- and primary production unit-based T Test, respectively).

During the survey most farmers reported the use of more than five types of pesticides during one cropping season. Efficacy was the most important selection criterion for 92% of the farmers, whereas only 6.4% regarded toxicity to themselves and consumers as their most important consideration in pesticide selection. None of the farmers reported that they were concerned about the toxicity for themselves or consumers 5–7 years ago. Almost 97% of farmers asserted that the types of pesticides presently marketed and used are much more diverse than in the past. In addition, 72% of farmers stated that pesticides are safer today than they were in the past based on their own observations and personal experiences. For instance, farmers mentioned that at present they feel less tired after spraying pesticides and that they find less or no aquatic animals dead after spraying compared with the past. This impression is contradicted by 12% of the farmers, who think that pesticides are currently more toxic compared with 5–7 years ago.

A large majority (62%) of the farmers interviewed were not able to determine the World Health Organization-classified toxicity of the five pesticides they use most often. The rest could determine the toxicity of some or all of these five types. Farmers who knew the toxicity of some types have mainly learnt this by heart on the basis of information acquired from their neighbors or from the retailers. Those who could determine the toxicity of all five types of pesticides relied on the color of the barcode on the pesticide package/bottle and they got additional information from

Table 3. The ten pesticides used most by farmers in Hanoi during two time periods.

Ai	Toxic class (by World Health Organization)	MP1			MP2		
		Frequency of use (%)	Ai quantity (%)	Value (%)	Frequency of use (%)	Ai quantity (%)	Value (%)
Insecticide							
Nereistoxin	Unknown	16.0	21.5	8.4	8.7	18.5	4.0
Abamectin	Unknown	10.3	0.3	13.3	11.2	0.1	12.3
Cypermethrin	II	9.3	2.9	8.0	3.2	0.5	2.4
Endosulfan	II	5.1	4.7	6.5	–	–	–
Fenobucarb	II	3.0	2.3	3.0	8.1	20.8	7.1
Acetamiprid	Unknown	–	–	–	7.5	0.7	6.1
Chlorpyriphos	II	–	–	–	4.1	4.8	5.1
Indoxacarb	Unknown	–	–	–	4.7	0.6	15.4
Permethrin	II	–	–	–	6.8	2.1	7.2
Fungicide							
Zineb	U	7.5	26.2	6.2	–	–	–
Validamycin	U	5.5	0.4	2.7	8.9	0.9	3.7
Mancozeb	U	3.1	7.3	5.1	–	–	–
Copper hydroxide	III	1.2	5.2	2.3	–	–	–
Herbicide							
Butachlor	U	3.0	3.1	1.6	4.3	10.7	5.2
Total		63.9	73.7	57.0	70.1	59.6	68.3

Table 4. Pesticide spraying practices of farmers in Hanoi during two time periods.

Number of pesticide combined for one spray	MP1		MP2	
	Frequency of application (%)	Ai quantity (%)	Frequency of application (%)	Ai quantity (%)
1	42.7	34.0	43.6	38.6
2	28.0	30.2	41.0	39.8
3	9.0	18.7	13.2	18.0
4	1.9	2.8	2.1	3.4
5	0.4	0.8	0.2	0.2
Undetermined	18.1	13.6	0.0	0.0

the pesticide labels. Pesticides that claimed to be biological were automatically considered safe by the farmers. Another tool farmers relied on in determining the toxicity of pesticides is the pre-harvest interval. The shorter the pre-harvest interval, the safer they considered the pesticide. Despite the fact that the majority of the farmers could not determine the toxicity of the pesticides they used, most of them were not really concerned about their toxicity as such. Up to 42% of the farmers said they take toxicity into account when they purchase and use pesticides.

According to the farmers' survey, up to 75% of the farmers apply a higher dosage than recommended and only 25% of the farmers stick to the recommended dose. Around 27% of the farmers always combine two or more different types of pesticides in each spray. Roughly 2% of the farmers said that they never use pesticides in a cocktail. The rest reported that they could cocktail pesticides when they find serious attacks of pests and diseases. Similarly, during the farm monitoring study, the application of 'pesticide cocktails' dominated the spraying practices of farmers. In terms of their frequency, the combination of two pesticides for one spray increased remarkably, from 28% in MP1 to 41% in MP2. Sometimes the cocktail even consisted of more than two different types of pesticides (in finished form) (Table 4).

Both the farmers' survey and the farm monitoring clearly showed that all (100%) farmers in the Red River Delta rely on pesticides as their main tool for controlling pests and diseases. However, next to pesticides, up to 42% of the farmers interviewed also apply other pest-controlling methods such as manual control, crop rotation and field clearing. In particular, 5% of the farmers reported that they apply crop rotation and soil treatment seasonally or periodically to reduce the development of pests and other diseases. According to farmers, clearing the fields after harvesting vegetables (or even without harvesting them if the market

Table 5. Average cost for one tank of pesticide in Hanoi in the second monitoring period (MP2).

Number of pesticide combined for one spray	Frequency of application	Average cost (in VND)	Standard deviation
1	552	4051.29	3641.33
2	519	5491.51	3806.95
3	167	7922.91	4959.04
4	27	9525.25	3456.05
5	2	11,537.13	329.20
Average	1267	5280.02	4149.09

price is too low) is nowadays done more often than in the past, because they witnessed a significant effect on reducing the expansion of pests and diseases. Also new methods are emerging. For instance, a farmer in Hai Duong province discovered by accident a biological method to control *Spodoptera litura*—an insect that has strong negative effects on vegetable production:

> 'Until two cropping seasons ago, after harvesting kohlrabi, I sprayed pesticides to kill the insects that remained in the soil, including *Spodoptera litura*. However, when I ploughed the soil in preparation of the next planting season, I found that the *Spodoptera litura* insects were highly concentrated in the few kohlrabi roots that were left in the field. So, I concluded that pesticides could not effectively control these insects since they live in the soil. During the next season when I found that the vegetable was damaged by the insects, I therefore collected kohlrabi leaves growing on other fields and put them on the soil beds to attract the insects. I started this job at about 4 or 5 pm and returned to my vegetable fields at 7 or 8 pm with a flash light and a tank. Kohlrabi leaves were carefully picked up and the insects were released into the tank by shaking the leaves. The leaves were then put back on the soil bed. Early next morning, I collected the insects from the kohlrabi leaves again. By doing so, I significantly controlled *Spodoptera litura* without using pesticides specifically for this insect. I did tell my neighbors and some of them have started to apply this controlling method as well.'

An example of less pesticide-based vegetable production is also found in Nam Dinh province. In some areas, farmers grow baby cucumber under contract with processing companies. At the early growing stage when the plant has only 2 to 3 leaves, it is often seriously attacked by leafminer. The conventional pesticide spraying method turns out to be less successful. For this, in recent years, instead of spraying pesticides, the farmers inject pesticide directly into pedicels of plant leaves. This pest control method not only helps farmers successfully control leafminer, but also save them up to 60% of pesticide quantity (in finished form), as revealed by farmers, as compared with the conventional method of spraying.

Factors influencing pesticide practices of farmers

As presented in the previous section, no statistical difference could be observed in quantity of pesticides used by farmers (per ha percropping season) when comparing 2002 and 2007. However, the study proved that there is a difference between the 2 years in terms of the value of the pesticides that farmers used (per ha per cropping season). This section will help to explain the different factors that play a role in farmers' daily decisions in selecting and handling pesticides.

The survey showed that farmers often judge the quality of the pesticides they apply on the basis of cash cost per tank of pesticide. For farmers in Hanoi, one tank worth 6000–7000 VND would be acceptable both in terms of their financial capacity and their perception of effective pest control under average circumstances. Farmers in Hai Duong, consider spending a little less, i.e., 5000–6000 VND for a tank, as acceptable. This perception of pesticide use based on financial expenditure can lead to the wrong application of pesticides, for instance, applying pesticide cocktails as mentioned above or using pesticides above/below the recommended dosage. For instance, in Dong Anh and Gia Lam district (Hanoi), we found examples of farmers who applied one package of Amate 150SC, which is technically suggested for treatment of about 120 m^2 of vegetable area, for more than 200 m^2! In order to save time and labor, some farmers increase the concentration of pesticide and reduce the volume of the tanks compared with the technical prescriptions for treating the crop.

In our pesticide monitoring study, we found that, based on the information from the 1267 cases of pesticides applied during MP2, the average amount spent by farmers for one tank of pesticides is 5280 VND (Table 5). Although somewhat arbitrary, we can assume that pesticides sold for less than 2000 VND package^{-1} (to be applied in one tank) are inexpensive. On the basis of this assumption, we found that 28.4% of the total number of tanks contained inexpensive pesticides. Of the 111 different types of pesticides (in finished form) used by the farmers that were monitored, 25 were bought for less than 2000 VND package^{-1}. The 25 cheap pesticides accounted for 26.4% of the total quantity of pesticide Ai, but only for 11.2% of the total pesticide cost. When farmers prioritize the reduction of risks from pests and diseases to save their crops, they tend to rely on pesticide cocktails. In general, the more pesticides are combined in the cocktail, the more expensive this is as well. Finally, farmers apply inexpensive pesticides for additional spray(s) if they

Table 6. Factors affecting farmers' selection and use of pesticides in two provinces (principal components analysis: rotated component matrix).

Variables	Factor/loading		
	Factor 1	**Factor 2**	**Factor 3**
Farmers' ability to classify pesticide toxicity	**0.86**	0.04	0.04
Farmers' concern for pesticide toxicity	**0.86**	0.08	−0.15
Technical training	**0.59**	−0.31	0.08
Farmers' perception on incidence of damage caused by pests and diseases	−0.09	**0.75**	−0.06
Farmers' perception on pesticide toxicity	0.04	**0.71**	0.07
Education level	0.20	−0.12	**0.77**
Number of information sources for pesticide selection and use	0.25	−0.14	**−0.69**
% of variance	28.27	16.73	15.78
Factor interpretation	Pesticide knowledge	Farmers' perception	Information sources

Variables indicated in bold values are considered for interpretation by the representative factor, $n = 125$. Bartlett's test of sphericity is significant at $P < 0.01$.

consider the previous application not as effective as expected.

A Principal Components Analysis applied on seven variables coded from 1 to 4, resulted in three major groups of interrelated variables explaining the use of pesticides. Factor 1 (% of variance: 27.77) can be interpreted as 'pesticide knowledge' of farmers. This factor is accounted for mainly by the variables *Farmers' ability to classify pesticide toxicity*, *Farmers' concern for pesticide toxicity* and *Technical training*. Farmers with more technical training are more capable of classifying pesticide toxicity and seem more concerned about pesticide toxicity in their selection and use. Factor 2 (% of variance: 16.53) can be interpreted as 'farmers' perception'. This factor is explained by two major variables: *Farmers' perception on incidence of damage caused by pests and diseases* and *Farmers' perception on pesticide toxicity*. Farmers who perceive that current problems of pests and diseases are more serious also perceive that current pesticides are more toxic than those in the past. It could be assumed that the higher the risks caused by pests and diseases are perceived, the more farmers intend to use toxic pesticides. Factor 3 (% of variance: 15.59) is interpreted as the 'information sources' based on which farmers make their selection and use of pesticides. There is a negative relation between the variables of *Education level* and *Information sources for pesticide selection and use*. This means that farmers of higher education level rely on fewer sources of information for their selection and use of pesticides. In this case, they preferably rely on their own knowledge, acquired from daily farming practices, rather than on external sources such as neighbors, retailers and/or extension staff (Table 6).

A discriminant analysis of the seven variables used for our factor analysis was carried out comparing 'safe vegetable' producers with their 'normal vegetable' colleagues and Hanoi with Hai Duong farmers. The discriminant analysis of safe vegetable versus normal vegetable growers gave high loadings for the variables *Farmers' ability in the classification of pesticide toxicity*, *Farmers' concern for pesticide toxicity* and *Technical training*. There is a statistically significant difference between these two groups of farmers ($P < 0.1$). More technical training for farmers under a safe vegetable program explains this difference. There is also a statistically significant difference between farmers in Hanoi and those in Hai Duong ($P < 0.01$). These two groups are not only significantly distinct in 'pesticide knowledge', but also in 'perception' on pesticide toxicity and the incidence of damage caused by pests and diseases, as well as the number of information sources to which farmers refer in their selection and use of pesticides (Table 7).

Conclusions

The institutional setting in Vietnam for a change in pesticide distribution and toward use of fewer and fewer toxic active ingredients is slow, but somewhat promising. A highly profitable market, with ineffective state inspection and enforcement, and poorly informed farmers that were strongly dependent on retailers and pesticide producers together created a difficult situation for environmental improvements in pesticide management. Nevertheless, this study found clear evidence for the presence of an increasing number of vegetable farmers in Vietnam that changed practices of pesticide use, because of the health risks associated with pesticides and economic trade-offs, i.e., between labor and pesticide costs. Especially farmers in Hanoi showed increased preference for using pesticides with shorter pre-harvest intervals and higher costs, which are perceived as indications for safer pesticides. This trend

Table 7. Differences in pesticide knowledge between farmer's groups in two provinces (discriminant analysis: structure matrix).

Variables	Loadings	
	Safe–normal vegetables	Hanoi–Haiduong
Farmers' ability to classify pesticide toxicity	**0.77**	**0.49**
Farmers' concern for pesticide toxicity	**0.75**	**0.31**
Technical training	**0.67**	**0.49**
Farmers' perception on pesticide toxicity	−0.18	**0.38**
Farmers' perception on incident of damage caused by pests and diseases	−0.06	**−0.33**
Number of information sources for pesticide selection and use	0.06	**−0.39**
Education level	−0.01	0.20

Variables indicated in bold are considered for interpretation by the representative factor, $n = 125$, valid cases = 76%. For safe–normal vegetables discriminant analysis, Wilks' Lambda = 0.87; $P = 0.09$ and for Hanoi–Haiduong, Wilks' Lambda = 0.76, $P < 0.01$.

goes together with a clear reduction in the use of pesticides with unknown Ais, which are often condemned as illegal and highly toxic in Vietnam. Although limited, this improvement in pesticide use can be considered a success, especially given the increasing intensification in vegetable production at the research sites (for instance in Dong Anh district, Hanoi, the cropping index increased from 1.41 in MP1 to 1.74 in MP2).

Farmers are remarkably concerned about the toxicity of the pesticides they use. Our study revealed that the selection and use of pesticides are, among others, influenced by the farmers' technical knowledge, their perception of the risks associated with pest and disease attacks and with pesticide toxicity and the information sources to which farmers have access. Red River Delta farmers seem to have developed from passive into reflexive users with respect to pesticide selection and application. Notably in Hanoi, farmers have become less dependent on pesticide retailers, both for their technical information and for financial support. Moreover, in certain cases, they are even 'whistleblowers' on the sale of illegal pesticides by these retailers. The combination of an increased awareness among farmers of the cost-effectiveness of pesticide use and of the negative effects of pesticides, with a somewhat more effective enforcement of state regulations, has contributed to the revealed shift toward the distribution and application of more expensive and safer pesticides, and to the decreased use of pesticides with unknown active ingredients.

But much still remains to be improved. Though parasitic and inexpensive pesticides account only for a small percentage of the total pesticide expenditure of farmers for all vegetable crops in MP2 (11.2%), they are responsible for a much higher percentage of the total quantity of active ingredients (26.4%), as shown in the results of our second farm monitoring study in Dong Anh district, Hanoi. These products do not contribute much to the control of pests and diseases, at least from retailers' and farmers' perspectives, but add heavily to the impact and burden on the environment and human health. Quick removal of these pesticides from the market via state intervention is thus technically and economically possible and could be strongly suggested. Otherwise, although farmers are increasingly getting rid of 'parasitic' pesticides while improving their knowledge and experience of these pesticides, it will take a long time until a substantial percentage of farmers decides to fully get rid of these pesticides.

The efforts by the Vietnamese authorities to promote 'safe vegetable' production practices, with relatively high costs[29], have achieved some results at the farm level. So far, this government program, with its extensive technical training provided to farmers, has led to differences in the 'pesticide knowledge' and 'pesticide cocktailing practices' of 'safe vegetable' farmers compared with 'normal vegetable' farmers. However, the differences in pesticide use practices between Hanoi and Hai Duong should be explained rather by the technical knowledge and financial capacity of farmers and the intensification of vegetable production than purely by governmental interventions, notably by differences in investments (e.g., in the so-called net houses, which protect plants (growing inside) from attacks of insects) and in the use of zoning areas for safe vegetable production. Future official programs on safe vegetable production should be based on a careful evaluation and analysis of the impacts of the program so far and, in particular, pay attention to other actors playing a role in successful improvements in practices of pesticide use.

Given the poor economic conditions of the small-scale and fragmented landholdings of Vietnamese farmers, and—to a lesser extent—the state of Vietnamese pesticide companies, a radical move away from pesticide use in the Vietnamese agricultural sector is not likely in the short term. Pesticides will, for the moment, remain of vital importance for Vietnam's agriculture in general and for vegetable production in the Red River Delta in particular. But a shift toward the reduction of pesticide use in vegetable production and the distribution of products with newer and safer compounds is possible and badly needed to protect human health and the environment. As shown above, this shift has already started. In particular, several innovations by farmers and—to a lesser extent—pesticide companies and retailers can be witnessed. These small shifts and innovations will certainly take time before gaining sufficient momentum and geographical spreading

throughout the Red River Delta region. The further integration of Vietnam into the world economy, as well as an active governmental intervention strategy, will hopefully result in Vietnam joining the international trend toward 'the gradual but relentless transition from chemical to *more environmental friendly and* biological pest control ...' (italic added)[30]. The process of greening pesticide distribution and use in Vietnam may be slow so far, but is most likely to continue in the foreseeable future.

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Effects of restorative agroecosystems on soil characteristics and plant production on a degraded soil in the Georgia Piedmont, USA

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Abstract

This work presents the results of a three-year field study of agroecosystems designed to restore soil organic matter (SOM) to degraded soils of the Georgia Piedmont. The systems combine a suite of management practices previously demonstrated to increase SOM when studied individually, and examine the effects of these techniques when used in combination in a cropping systems context on soil characteristics, crop production and weed biomass. The systems' components include organic management, alley cropping with perennial legumes, conservation tillage, use of winter cover crops, straw mulch and two compost application rates. Vegetable crops grown were a rotation of okra, hot pepper and a corn and winter squash intercrop. The systems were not able to maintain soil C or N without the addition of compost. Systems incorporating alley cropping, organic management, conservation tillage and compost maintained soil C, and increased in soil C when mulch was not applied. In organic, conservation tillage without alley cropping, soil C did not change significantly, even with annual 44.8 Mg ha^{-1} of compost additions. Patterns for soil N followed those of soil C. The study demonstrated that alley cropping can maintain and sequester soil C and N beyond organic conservation tillage alone, and more than conventionally tilled, chemically fertilized treatments. Crop yields did not vary by treatment due to high variation within treatments. Winter cover crop residue provided an effective weed barrier for 4 to 6 weeks in the spring, but additional hand weeding was required throughout the summer. The results of this systems-level study demonstrated interactions between management practices when used in combination that would not have been observed when studied individually. It also demonstrates that agroforestry techniques, conservation tillage and compost applications can increase soil C in degraded, clayey soils while they are in cultivation.

Key words: agroforestry, organic agriculture, conservation tillage, soil organic matter, restorative agriculture

Introduction

In recent years, there has been an increasing recognition of the impacts of industrialized food and fiber production on soils, waters and the atmosphere. The extensive tillage commonplace in industrial agriculture alters soil food webs[1], increases nitrogen losses[2] and erosion[3], depletes soil carbon[4–6] and has been the source of surface and groundwater nitrate[7] and other nutrient contamination[8,9]. In the southeastern US, centuries of row cropped monocultures have eroded vast tracts of surface soil horizons. The exposed, heavily weathered subsoil often lacks any appreciable organic matter or available nutrients[10]. In addition to this land use legacy, the subtropical climate in the region provides a myriad of management challenges. The climate is hot and humid with abundant rainfall, thus organic amendments and soil organic matter (SOM) decompose rapidly, and pest, pathogen and weed pressures are high. Dealing with this combination of historical, edaphic and climatic factors is a challenge for sustainable agriculture.

SOM has been identified as a 'keystone' property driving above- and below-ground productivity[11], and is a holistic indicator of soil quality in subtropical climates[12,13].

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A number of management techniques have been proposed to protect and restore SOM, or its chief constituent, soil organic carbon (SOC). These include the use of cover crops, perennial legumes, conservation tillage and composts. The benefits and disadvantages of these techniques in the southeastern US are reviewed below.

Winter cover crops have proven effective in increasing SOC[14,15]. However, incorporating cover crop residues via tillage may negate potential SOM gains, due to the rapid decomposition of incorporated residue[4,14,15]. Incorporation of leguminous residues may cause early season N losses due to rapid decomposition of nitrogenous residues[16].

Alley cropping (AC) is a technique where hedgerows of trees or shrubs are planted between rows, or alleys, of crop plants[17]. This technique is often practiced in the tropics where leguminous hedgerow species are used as perennial source of crop fertility, animal fodder and erosion control[18–20]. In these systems, shoots of hedgerow plants are coppiced, and the pruned branches applied as a mulch and green manure for adjacent crop plants. This application may have utility in the southeastern US, where hedgerows have the potential to produce large quantities of biomass due to the subtropical climate. Jordan[13] hypothesized that AC systems in the Southeast could reduce off-farm inputs, aid in weed suppression, control erosion and tighten nutrient cycles. However, AC systems can be land and labor intensive. Hedgerows may occupy 25% or more of available cropland[21] and require labor to establish and manage. As such, previous works have concluded AC may be best suited for labor-intensive operations, such as organic and high-value horticultural crops[10,13,21–23].

Conservation tillage has been shown to increase yields and SOM, reduce nutrient pollution[24], and to decrease erosion[3,25]. However, conservation tillage is often dependent on herbicides for weed management and termination of cover crops. These chemicals have been shown to move beyond the 'farm gate', even in conservation tillage systems[26].

Organic agriculture is not widely adopted in Georgia[27], but research in the northeastern US has demonstrated organic practices can increase soil C and produce yields comparable to those of conventional agriculture[28,29]. In organic agriculture, crop fertility needs are often met through application of composts, cover crops, animal manures, or mineral deposits in sand or gravel dusts[30]. These techniques can require less fossil fuel inputs than conventional agriculture[28], but may still experience high nutrient losses[28,31] due to extensive tillage and application of nitrogenous organic amendments. While organic agriculture may be considered 'low external input' in comparison to conventional agriculture[32], nutrient and pest management inputs may come from far off-farm, and have higher labor costs[28,30].

As reviewed, alley cropping, conservation tillage, winter cover cropping and organic farming practices have been shown to increase SOM and address other aspects of soil quality in the southeastern US. However, they are most often studied individually and not in combination. The objective of this study was to design cropping systems that incorporate a suite of these techniques and to study their effects in combination on SOM, agronomic soil quality and plant production. To our knowledge, this is the only organic, conservation tillage, agroforestry experiment in the southeastern US.

Materials and Methods

Site description

The study site is located in the Georgia Piedmont, near Athens, Georgia, USA (33°57′N 83°19′W). Soils on the research farm have been in cultivation since 1864. The soil at the experimental site is a Pacolet sandy clay loam (kaolinitic, thermic typic hapludults). The A horizon was entirely eroded away as a result of nearly a century of cotton farming. The surface soil was a remnant B-horizon of heavily compacted red clay. Intense cultivation and grazing on the site ceased in 1993, when management shifted to a mowed fallow. This degraded site was chosen to test the methods on an extremely poor soil in the Georgia Piedmont. In 2001, leguminous hedgerows of *Albizia julibrissin* (mimosa) were planted 5 m apart along an east-facing slope on the site. Between 2001 and 2004, the alley ways were planted with a variety of vegetables and cotton. This work commenced in 2004.

Experimental design

The four experimental cropping systems were:

1. AC with organic vegetables using strip tillage (AC),
2. organic vegetables using strip tillage [no alley cropping and organic strip tillage (OST)],
3. conventionally fertilized, conventionally tilled (CT) vegetables, and
4. a mowed fallow (fallow).

The AC and CT cropping systems and the fallow were established in 2004 and studied for 3 years, and the OST system was established in 2005, and studied for 2 years. At the start of this experiment in summer 2004, the alleys were surface tilled with a roto-tiller to a depth of 5 cm. A summer cover crop of sunn hemp (*Crotalaria juncea*) was broadcast sown and killed with a mechanical grass roller (a 'roller crimper') in September.

In early October of each following year, summer vegetation was killed using the roller crimper. A blend of legume and grass cover crops consisting of crimson clover [*Trifolium incarnatum* (20.17 kg ha^{-1})], Austrian winter pea [*Pisum sativum* (22.61 kg ha^{-1})] and winter rye [*Secale cereale* (53.80 kg ha^{-1})] was broadcast sown over the summer vegetation. In the spring when crimson clover was in full flower and winter rye was at 'soft dough' stage (early mid April), winter cover crops in the AC and OST treatments were mechanically killed with the roller crimper. Cover crop residues were allowed to decompose for

Table 1. Description of experimental treatments.

Cropping system	Treatment name	Treatment description	Treatment progression	Number of replicates
Conventional	Conventional	Conventional	Disk and rototill, starter 10-10-10 fertilizer, side dress 10-10-10, hand weeding of summer vegetable crop	8
Fallow	Fallow	Fallow	Fallow of mowed pasture grass, no fertilization or irrigation	6
AC	AC1	*Albizia* hedgerows + winter cover crop	Winter cover crop>summer vegetable crop/*Albizia* pruning	4
AC	AC2	AC1 + mulch	Winter cover crop>summer vegetable crop/*Albizia* pruning/straw mulch	4
AC	AC3	AC1 + spring compost	Winter cover crop>spring compost application/summer vegetable crop/*Albizia* pruning	4
AC	AC4	AC1 + spring compost + mulch	Winter cover crop>spring compost application/summer vegetable crop/*Albizia* pruning/straw mulch	4
AC	AC5	AC1 + spring and fall compost	Winter cover crop/fall compost application>spring compost application/summer vegetable crop/*Albizia* pruning	4
AC	AC6	AC1 + spring and fall compost + mulch	Winter cover crop/fall compost application>spring compost application/summer vegetable crop/*Albizia* pruning/straw mulch	4
OST	OST1	Winter cover crop + mulch	Winter cover crop>summer vegetable crop/straw mulch	4
OST	OST2	OST1 + spring compost + mulch	Winter cover crop>spring compost application/summer vegetable crop/straw mulch	4
OST	OST3	OST1 + spring and fall compost + mulch	Winter cover crop/fall compost application>spring compost application/summer vegetable crop/straw mulch>	4

> Indicates the treatment progression. / Indicates concurrent treatments.

approximately 2 weeks, and then plots were strip-tilled to create a planting furrow 15 cm wide by 15 cm deep. The conventionally tilled treatment was disked and roto-tilled approximately 1 week prior to vegetable planting.

Vegetable crops were direct seeded (years 1 and 3) or transplanted (year 2) into the furrow by hand. All vegetable crops were irrigated using drip irrigation, which was installed prior to planting each spring and removed each fall. The sequence of summer vegetables began with okra (*Abelmoschus esculentus*, 'Clemson spineless') in year 1, and was followed in year 2 by hot peppers (*Capsicum annum*, 'Long cayenne') and corn and winter squash intercrop (*Zea mays*, 'Reid's yellow dent' and *Cucurbita moschata*, 'Waltham butternut') in year 3. All plots were hand weeded throughout the growing season.

The AC system consisted of six treatments with varying rates of compost application, and with and without straw mulch (Table 1). Hedgerows were pruned one to three times each summer to a height of 1 m when they began to shade crop plants. Prunings were evenly applied to the cultivated plots in adjacent alleys. AC plots were 5 m wide (the spacing between the hedgerows) by approximately 6 m in length. The OST system consisted of three treatments with varying rates of compost application to correspond with the AC cropping system, with all treatments receiving straw mulch. OST plots were 5 m by 5 m. Compost consisted of poultry litter and wood chips. Straw mulch consisted of wheat straw in year 1 and pasture hay in years 2 and 3. Compost and straw mulch were applied by hand in all treatments. Conventional treatments were broadcast fertilized with inorganic fertilizers (10-10-10 percent N, P and K, respectively) in bands adjacent to crop rows within 10 cm of crop plants. Rates of application were according to University of Georgia (UGA) Cooperative Extension fertilizer recommendations for each crop[33–36]. All treatments were randomly distributed within their respective cropping system. Complete treatment descriptions are listed in Table 1.

Soils were sampled in the fall of each year prior to fall compost application and sowing of the winter cover crop. Soils were sampled from 0 to 5 cm and 5 to 15 cm for C, N and pH, with three soil cores collected randomly from the middle portion of each plot and bulked for a single analysis. C, N and pH samples were oven dried at 50°C to a constant mass, passed through a 2 mm sieve, and ground on a Spex mill to a particle size $< 250\,\mu m$. Samples were analyzed for total C and N by micro-Dumas combustion assay. pH was assayed from a solution of equal volumes of soil and water using an Fischer Scientific Accument 25 pH meter. Bulk density was sampled from 0 to 5 cm in the fall of each year, with one sample collected from the middle portion of each plot, outside of the planting furrow. Aggregate stability was sampled in the spring of 2004 in the AC treatments, and in the fall of 2005, 2006 and 2007 in all treatments. Three 0–5 cm cores were collected randomly from each plot, air dried and bulked for a single analysis per plot. Water stable aggregates (WSAs) $>250\,\mu m$ were determined by wet

sieving by hand, according to USDA Soil Quality Test Kit protocol[37].

Soils were sampled for microbial biomass six times over 3 years, in the winter (February) and spring (late April) of each year to obtain low and high microbial activity, respectively. Three soil cores from 0 to 5 cm were collected per plot, placed on ice at collection and refrigerated prior to processing, which occurred within 24 h of collection. Samples were hand sorted to remove roots and rocks greater than 2 mm. Hand sorting was preferred to the passing samples through a 2 mm sieve, as samples from the initial sampling date soils were too wet and clayey to pass through the sieve, thus succeeding processing was handled identically. Soil microbial biomass was determined by the chloroform fumigation extraction method[38]. Samples were fumigated for five days to maximize extraction of microbial biomass C in wet, clayey soils[39]. Extracted samples were stored frozen prior to analysis on a Shimadzu 500 Total Organic Carbon analyzer. Microbial biomass C was calculated as the difference between fumigated and non-fumigated samples using a k_c value of 0.45[40].

Vegetation was sampled in the spring and fall, corresponding to the end of the winter and summer cropping seasons. One 0.25 m^2 sample was collected randomly from the middle portion of each plot. Above- and below-ground biomass was collected, with above-ground biomass reported in this work. Vegetation samples were dried at 50°C to a constant mass and sorted into weed and crop categories to determine if the vegetation community had changed between years. Biomass was recorded for each category, and then bulked into a single sample per plot for nutrient analysis.

Crop yields were recorded throughout the summers of 2005 and 2006 from four marked plants per plot. Fruits from one of the marked plants in each plot were collected and dried throughout the season, and combined by plot at the end of the season for a single nutrient analysis. In 2007, all winter squash fruits in each plot were weighed for yield determinations, due to the difficulty in isolating individual squash plants. One fruit per plot was collected for nutrient analysis. Corn yields were estimated from kernel counts on 10 ears of corn per plot and total number of corn plants per plot. Yield calculations assumed an average of 90,000 kernels $bushel^{-1}$ and average mass of 24.36 kg $bushel^{-1}$, which was determined by dry weights of a known quantity of oven dry kernels. Corn grain nutrient content was obtained from ears collected in 0.25 m^2 vegetation samples.

Hedgerow prunings and straw mulch additions were sampled at the time of application, with one, 1 m^2 sample collected from the middle portion of each plot. Except for winter squash fruits, all amendment and crop yield samples were dried in a 50°C drying oven to a constant mass. Winter squash fruits were dried in an American Harvest Food Dehydrator to a constant mass, due to samples molding in the drying oven. Vegetation samples were homogenized on a Wiley mill with a 2 mm screen. Subsamples were ball-milled to less than 250 µm particle size on a Spex mill, and analyzed for C and N by micro-Dumas combustion assay. All analyses were conducted at the UGA School of Ecology Analytical Chemistry Laboratory.

Statistical analysis

Data were analyzed using the MIXED procedure with restricted maximum likelihood (REML) in SAS Version 9.1 for PC[41] as a randomized block with sampling date as the repeated measure, plot as a random variable. Treatment effects were nested within cropping system (AC, OST, CT and Fallow). A nested experimental design was necessary to keep hedgerow roots isolated within the AC system. Differences between treatments with significant interactions were determined by pairwise differences.

Results

Soil characteristics

Bulk density (g cm^{-3}) from 0 to 5 cm differed significantly by treatment over time ($P = 0.0332$). AC treatments not receiving mulch (AC2, AC4 and AC6) decreased significantly over 3 years. Bulk density in other AC treatments also decreased over time, but trends were not significant. OST treatments receiving mulch and 0 or 22.4 Mg ha^{-1} of compost, Fallow and CT treatments did not change significantly. Bulk density in OST3 increased significantly over 3 years (Fig. 1). Mean values for all treatments were uncharacteristically low for the region.

WSAs >250 µm in the 0–5 cm soil depth changed significantly over time ($P < 0.001$) but not by treatment. Mean WSAs from all treatments increased from year 1 (65.97 ± 7.12%) to year 3 (80.17 ± 1.66%), then decreased from year 3 to year 4 (58.45 ± 6.17%).

pH was higher in the 0–5 cm depth than in 5–15 cm depth ($P < 0.0001$), with significant treatment by time interactions ($P < 0.0001$). Irrespective of depth, AC treatments receiving compost (AC3–AC6) and the CT increased in pH (Fig. 2). OST and Fallow treatments did not change significantly.

Gravimetric soil C and N content (%C and %N) were converted to volumetric content using bulk density values from 0 to 20 cm samples that were taken after the study had concluded (data not shown). Four samples were taken from each cropping system (AC, OST, CT and Fallow) and the mean value used for both 0–5 cm and 5–15 cm calculations. This estimation was necessary, as bulk density was sampled only from 0 to 5 cm during the course of the field study. Soil C was greater from 0 to 5 cm than from 5 to 15 cm in all treatments ($P < 0.0001$) and significantly different by time ($P < 0.0001$) and treatment by time ($P = 0.0009$). Depth by time interactions were significant ($P < 0.0001$), with soil C increasing from 0 to 5 cm and decreasing from 5 to 15 cm. Irrespective of depth, CT and AC treatments without compost additions (AC1 and AC2) decreased significantly over 3 years (Fig. 3). The OST treatments also decreased, but the trend was not significant. The only

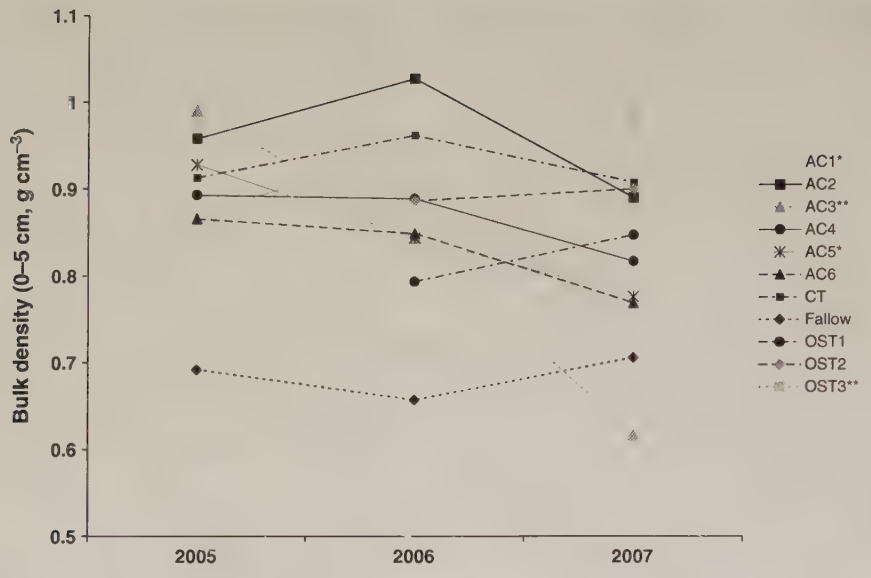

Figure 1. Soil bulk density (g cm^{-3}) from 2005 to 2007. *Indicates significance at $P \leqslant 0.10$. **Indicates significance at both $P \leqslant 0.10$ and $P \leqslant 0.05$.

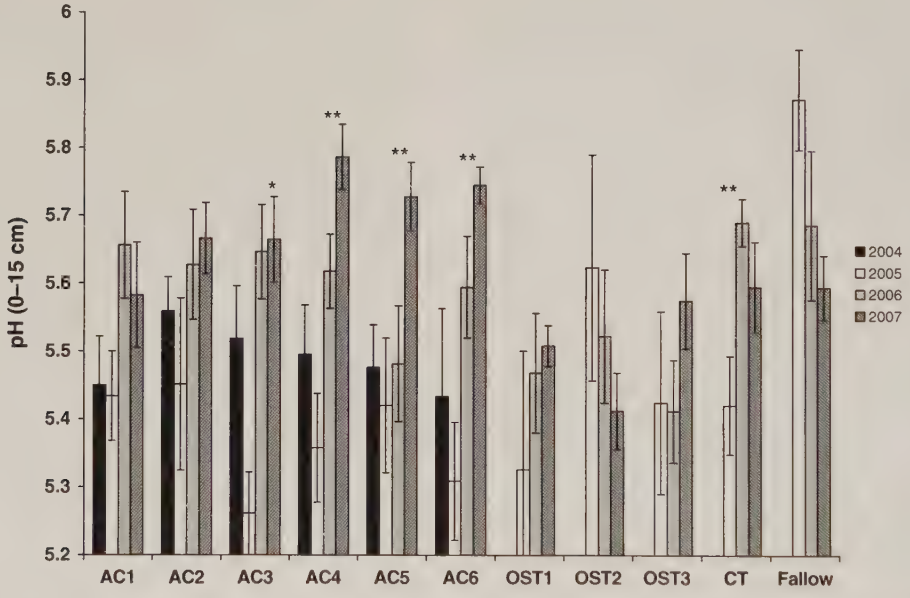

Figure 2. Soil pH (0–5 cm) by treatment from 2004 to 2007. *Indicates significance at $P \leqslant 0.10$. **Indicates significance at both $P \leqslant 0.10$ and $P \leqslant 0.05$.

significant increases in soil C were in the Fallow and AC5, which received 44.8 Mg ha^{-1} of compost annually and not mulch. Treatments receiving mulch, irrespective of the quantity of compost and/or alley cropping, did not increase significantly in soil C. Soil microbial biomass carbon (μg C g^{-1} dry soil) fluctuated seasonally, with higher biomass C in spring than in winter ($P = < 0.0001$), but did not differ significantly by treatment or by treatment over time (data not shown).

Changes in soil nitrogen (N) were significant by treatment ($P < 0.0001$) and were higher from 0 to 5 cm than 5 to 15 cm in all treatments ($P < 0.0001$). Depth by time interactions were significant ($P < 0.0001$), increasing from 0 to 5 cm while decreasing from 5 to 15 cm over the course of the study. Soil N differed significantly by treatment over time ($P = 0.0016$), with trends following the same pattern as soil C. However, the only significant increases in soil N were in AC treatments receiving 44.8 Mg ha^{-1} of compost but not mulch (AC5) and the Fallow. The only significant decreases were in the AC treatment without compost (AC2) and in the CT treatment (Fig. 4).

Vegetation characteristics

Spring vegetation results include data from 2005 and 2007, as 2006 samples rotted in storage prior to analysis. Across

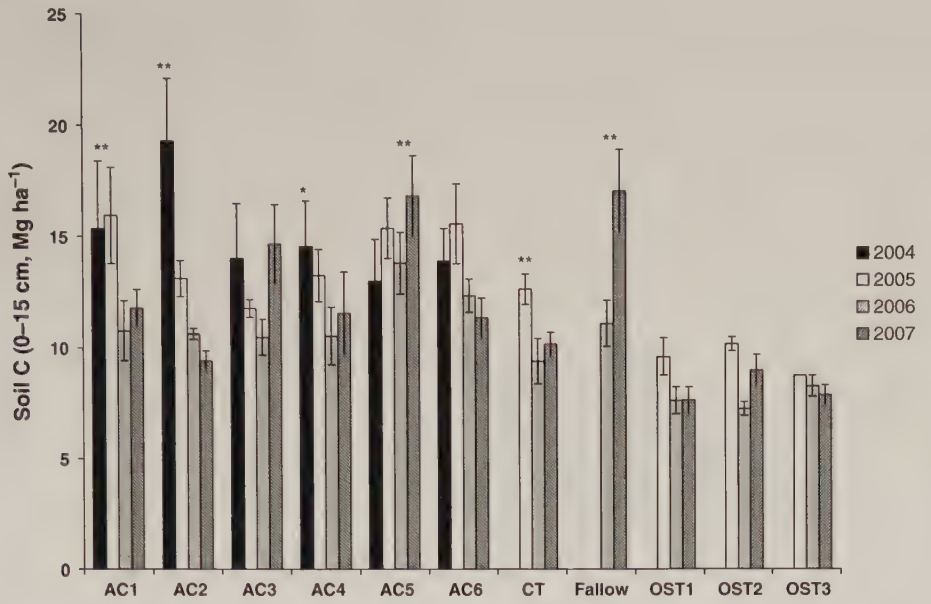

Figure 3. Soil %C (0–15 cm) by treatment from 2004 to 2007. Values reported are mean treatment values ± S.E. *Indicates significance at $P \leqslant 0.10$. **Indicates significance at both $P \leqslant 0.10$ and $P \leqslant 0.05$.

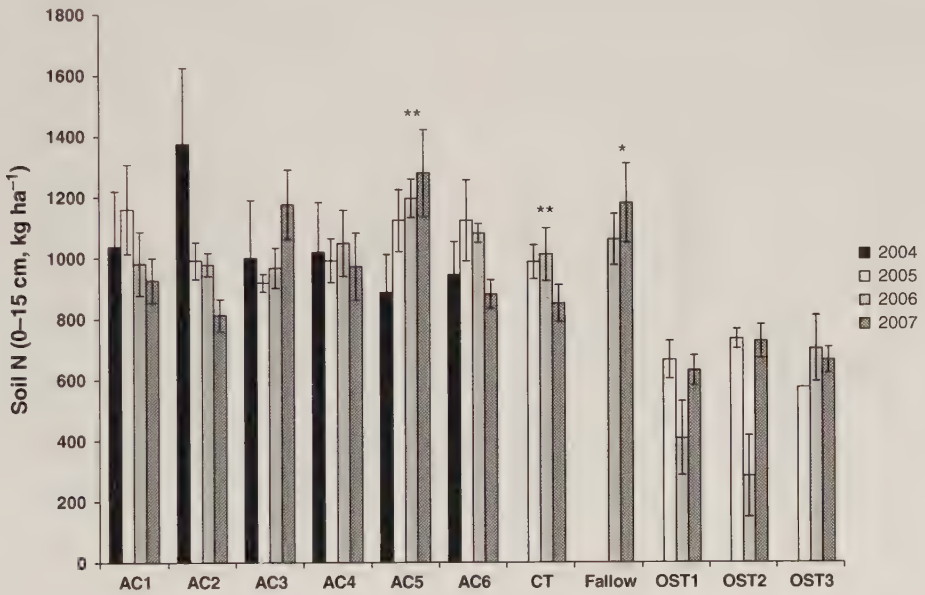

Figure 4. Soil %N (0–15 cm) by treatment. Values reported are mean treatment values ± S.E. *Indicates significance at $P \leqslant 0.10$. **Indicates significance at both $P \leqslant 0.10$ and $P \leqslant 0.05$.

all years, cover crop biomass was greater than fallow vegetation in the CT and fallow treatments ($P < 0.0001$). Cover crop biomass declined in all treatments from 2005 to 2007 ($P = 0.0056$), but treatment by date interactions were not significant (data not shown). Cover crop N (kg ha^{-1}) results had significant treatment by date interactions ($P = 0.0374$), with declining N production in virtually all AC treatments (Fig. 5). Declines in AC treatments receiving compost (AC3–AC6) were less precipitous than those without compost. Spring weed biomass increased significantly from 2005 to 2007 across all treatments ($P = 0.0135$), from 64.87 kg ha^{-1} (0.99% of spring biomass) to 858.91 kg ha^{-1} (16.00% of spring biomass) in the AC treatments. Although treatment effects were not significant, mulched treatments had considerably less spring weed biomass.

Fall vegetation biomass (kg ha^{-1}) consisted of crop plants and weeds harvested at the end of the summer growing season. Crop biomass (kg ha^{-1}) differed significantly by date ($P < 0.0001$) and treatment ($P = 0.0368$), generally with greater biomass in mulched than non-mulched treatments. All AC and OST treatments had greater crop biomass than the CT treatment. Fall weed biomass decreased significantly over time ($P = 0.0549$) and

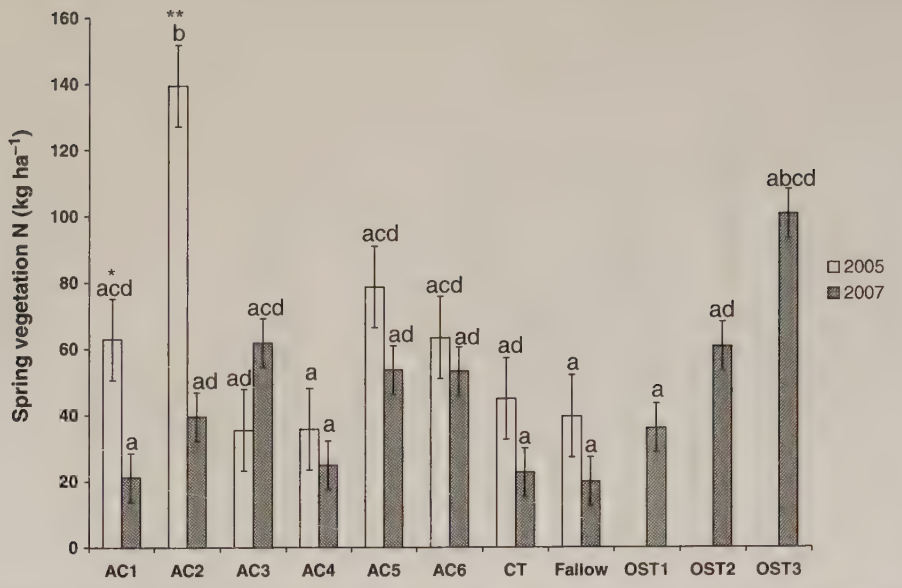

Figure 5. Spring vegetation above-ground biomass N (kg ha^{-1}) by treatment. Values reported are mean treatment values ± S.E.

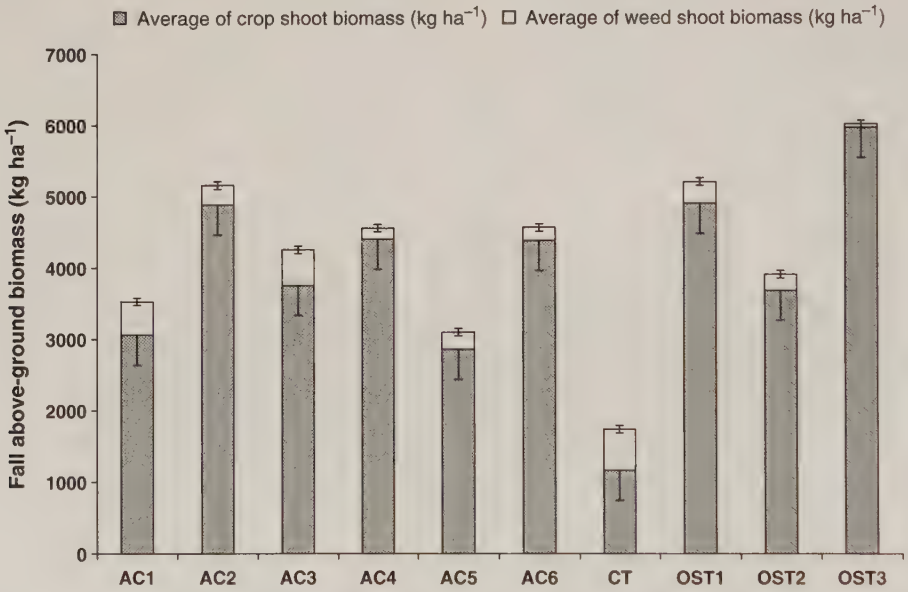

Figure 6. Fall crop and weed above-ground biomass (kg ha^{-1}) from 2005 to 2007. Values reported are mean treatment values ± S.E.

by treatment ($P = 0.0054$). Across all years, mulched treatments had lower weed biomass, and by the final sampling date weeds in mulched treatments were nearly non-existent (Fig. 6). Crop yields (fruit biomass) differed significantly by year ($P = 0.0002$), due to morphological differences in the crops in the rotation. Yield differences were not significant by treatment due to high variation in the data. Mean crop yields are presented in Table 2.

Biomass of hedgerow prunings differed significantly by date ($P < 0.0001$), with greater biomass from the first annual pruning than succeeding prunings. Corresponding C and N inputs (kg ha^{-1}) from the pruned biomass varied significantly over time ($P < 0.0001$ and $P < 0.0001$, respectively), as did the C/N ratio ($P < 0.0001$). During the 2005 season, biomass and C/N ratios declined over the course of three pruning dates. In 2006, biomass and C/N ratios increased from the first to the second pruning. Only one pruning was necessary in 2007, as a late spring frost killed developing mimosa shoots and a severe summer drought led to very slow shoot growth. Mean values for each pruning date are presented in Table 3.

Discussion

The only significant decreases in surface soil bulk density were in AC treatments without mulch. However, our sampling is not representative of bulk density throughout the study system, as samples were only taken from between

Table 2. Annual crop yields by treatment. Values reported are treatment mean yields (kg ha^{-1}) ± standard error (S.E.).

Treatment	Okra	Hot peppers	Corn/winter squash intercrop
AC1	3491 ± 1284	5823 ± 218	554 ± 293
AC2	4007 ± 561	5524 ± 799	2277 ± 383
AC3	3376 ± 841	6364 ± 1022	2398 ± 515
AC4	3852 ± 1497	3759 ± 826	1664 ± 530
AC5	4362 ± 802	5689 ± 1322	3467 ± 745
AC6	4505 ± 2084	3199 ± 994	2791 ± 877
CT	2598 ± 366	3119 ± 504	3000 ± 846
OST1		3793 ± 1605	4535 ± 1946
OST2		2988 ± 1492	4160 ± 1247
OST3		4839 ± 768	3566 ± 1045
All treatments	3535 ± 360	4633 ± 272	2718 ± 255

crop rows and not in cultivated furrows. This sampling technique was used to reduce variation due to differences within and between rows and minimize soil removal on relatively small plots, but as a result does accurately reflect change within the strip tilled planting rows, approximately 18% of the plot area. In the sampled between-row space, bulk density decreased in all AC treatments and increased in all OST treatments, suggesting AC-based systems may reduce soil compaction to a greater extent than analogous systems without perennial legumes. Long-term, deeper sampling with increased sample size would better illustrate the significance of these trends. Similarly, soils were sampled for C, N and pH randomly within the middle portion of each plot without consideration of whether the sample was collected within or between tilled rows. Thus, our results reflect the error associated across the entire plot, and are not weighted with values within and between rows.

Soil aggregate stability (WSAs>250 μm) results are probably a function of interactions between microbial response to organic inputs and climate. As observed in the first 2 years of the study, we would expect aggregate stability to increase with the addition of organic amendments and a resulting increase in soil microbial activity. However, in 2007 the region experienced a historic summer drought, which deteriorated to the 'exceptional' level, a condition expected only once every 100 years[42]. At the final sampling date, aggregate stability decreased in all treatments, as soils were exceedingly dry and friable at the surface with presumably little microbial activity.

While pH increases in AC treatments were incremental, they demonstrate that this technique in combination with conservation tillage can increase soil pH beyond analogous treatments without perennial legumes. pH increases on the CT treatment are probably due to greater crop and weed vegetation inputs relative to the sparse fallow vegetation that covered the site when this study began.

We initially hypothesized that the compost and mulch additions would have additive effects in increasing soil C. However, our results indicate interactions (non-additive effects) when these techniques are used in combination; interactions that are of ecological and economic relevance. In both the AC and OST systems all treatments receiving mulch either declined significantly or did not change, even with the addition of large quantities of compost. However, in non-mulched treatment receiving identical compost applications, soil C increased to a much greater extent, increasing significantly at the 44.8 Mg ha^{-1} annual application rate. We hypothesize that the increased moisture retained under the straw mulch increased decomposition rates relative to non-mulched treatments, to the extent that there were not significant changes in soil C after 3 years of the highest level of compost addition when mulch was present. This interaction may be particularly pronounced in the southeastern US, where hot, humid summers create high evapotranspiration rates that rapidly dry surface soils, decreasing microbial activity and consequently decomposition rates. Additionally, compost was required to maintain soil C in AC treatments, as treatments not receiving compost (AC1 and AC2) declined significantly.

These results are of economic significance to growers in the region. It is a common organic farming practice to apply straw mulch for weed suppression, particularly if tillage is minimized. However, mulching may negate increases in SOM from any economically practical level of compost application, and without a corresponding consistent increase in crop yields. As many small, diversified organic farmers in the region describe themselves as labor-limited[43], the benefits of mulching to reduce weeding labor may outweigh the potential to more efficiently sequester soil C and N, but will also increase compost costs for years to come. The production economics of this study are presented in Jacobsen and Escalante[44].

Throughout the course of the study soil C and N were generally higher in the AC system than the OST. Differences in initial conditions may be explained by the establishment period of the mimosa hedgerows, which were planted 3 years prior to initiation of this work. During this time, inputs from occasional hedgerow prunings, root sloughing, and crop and weed residues may have contributed soil C and N. Differences in initial conditions aside, soil C in AC treatments increased to a greater extent than in analogous OST treatments. That is, changes in soil C within treatment over time were greater in AC than OST treatments that differed only by the inclusion of perennial legumes (AC2 versus OST1, AC4 versus OST2 and AC6 versus OST3). These results indicate that on degraded soils, AC can sequester soil C more rapidly than organic, conservation tillage systems alone.

It is well established that conservation tillage conserves soil C[3,4,45]. However, increases in soil C have also been observed in organic farming systems that are tillage-dependent[28,46]. This is probably due to incorporation of high levels of organic amendments and long crop rotations, resulting in a rate of sequestration that outpaces decomposition. While our work utilizes conservation tillage, it is unclear whether some minimal incorporation of organic

Table 3. *Albizia* hedgerow pruning biomass. Values reported are means ± S.E.

Pruning date	June 22, 2005	August 12, 2005	September 22, 2005	June 25, 2006	September 1, 2006	September 17, 2007
Albizia mean biomass ($kg\,ha^{-1}$)	2780 ± 540	635 ± 95	578.57 ± 56	1245 ± 24	1223 ± 142	1625 ± 177
N ($kg\,ha^{-1}$)	75 ± 13	20 ± 3	16 ± 2	30 ± 4	37 ± 4	42 ± 4
C ($kg\,ha^{-1}$)	1242 ± 243	279 ± 42	259 ± 25	556 ± 75	541 ± 62	751 ± 81
C/N ratio	16	13	17	19	15	18

amendments would have increased soil C at deeper soil depths. A mechanistic analysis of the fate of amendment-derived nutrients under conservation and traditional tillage regimes would aid in making such conclusions.

The rationale for using mimosa in this study, although it has been considered invasive[47], was because the hedgerows were 3 years old at the initiation of this work and would be indicative of the production potential of a maturing system. Current research and extension work related to this study utilizes a native shrub *Amorpha fruticosa* (http://www.springvalleyecofarms.org). It appears from the declining number of pruning events over the course of this study that the hedgerows were declining in productivity. However, the quality (C and N content) and quantity (biomass) of mimosa prunings were probably a function of plant response to pruning and precipitation. Biomass from the first pruning in 2005 consisted of many large branches as the plants had not been pruned regularly since establishment. The resulting growth was prolific, as new above-ground growth was supported by a well-established root system and summer precipitation was abundant, near the regional average. In 2006, hedgerows produced less biomass than in the preceding year, probably due to below average rainfall and heavy pruning in the previous year. In both years, prunings from the second coppicing were more lush and nitrogenous than the first. Prunings in 2007 severely underestimate the production potential due to frost and drought damage the plants, as previously discussed.

Average annual N inputs from mimosa prunings varied from 42 to 111 $kg\,N\,ha^{-1}$, but are probably underestimates of total C and N inputs from the hedgerows. Root-derived inputs have been hypothesized to contribute significant quantities of additional C and N in AC systems, including root exudates and large pulses of dying fine roots that may senesce after pruning ('root sloughing')[48]. Additional above- and below-ground inputs may also come from seasonal leaf senescence in the fall[49].

It was initially theorized that the mimosa prunings would produce sufficient biomass to create a mulch layer that would aid in weed suppression[13]; organic farmers have identified weed management as their biggest management challenge[50]. However, the fine leaflets fell from the rachis of the compound leaf with 48 h of pruning, and the sparse woody material left behind was unable to suppress weeds. It is possible that with less space between hedgerows, and thus greater biomass production, the prunings would have been able to suppress weeds more effectively. The hedgerows in this experiment were planted 5 m apart, corresponding to the 4–6 m spacing most common in the tropical alley cropping systems[51]. Closer hedgerow configurations would need to be evaluated in light of the corresponding reduction in available cropland, additional labor to prune more plants, and the effects on residue quality produced by the increased pruning frequency required to prevent closer hedgerows from shading crop plants.

Spring weed biomass increased in the AC system due to a buildup of pernicious early season weeds, such as Carolina horse nettle (*Solanum carolinense*), crab grass (genus *Digitaria*) and annual ryegrass (*Lolium multiflorum*). More diligent, timely weed management in the early season and the use of larger transplants that would close the plant canopy faster could have minimized this problem. However, tillage is considered the most effective method of weed suppression in organic farming[52]. Successful weed management in organic, conservation tillage systems requires continuous effort throughout the year, beginning with dense spring cover crop production to create thick, weed suppressing mulch, followed by timely transplant and quick establishment of crops[53,54]. The cover crop provided an effective weed barrier for 4–6 weeks after roller crimping, but the time required for crop canopy closure was longer than the period of weed suppression, which resulted in a window for weed establishment. Weeds declined in the fall, as mature crop plants out competed weeds, and as the late summer weed community shifted from spring grasses toward easier to manage forbs.

Declines in spring vegetation (cover crop) biomass production are probably due to decreased available nutrients at the end of the summer cropping season. Declines in biomass production were less in treatments receiving fall compost than those without. Cover crop biomass was greater in mulched treatments, indicating that the residue layer did not have deleterious effects on succeeding cover crop growth.

Yield results did indicate significant differences in treatments over time, but trends observed in the field have important management implications. In 2005, okra yields in mulched treatments were higher than their non-mulched counterparts. Okra is susceptible to few soil-borne pathogens, and thus increased moisture content under mulch benefited the crop. Yield results in 2007, a drought year, showed similar trends. However, in 2006, yields in the

mulched treatments were lower than their non-mulched counterparts. The pepper plants in mulched treatments had a higher incidence of *Fusarium* wilt, with high plant mortality in the late season. It is possible the wetter, organic matter-rich soil under the mulch led to a proliferation of this fungal disease. These results indicate that the use of mulch in addition to no-till residues may increase soil-borne pathogen pressure in wetter years with disease-susceptible crops. No disease pressure was observed in the no-till residue without additional mulch.

Conclusions

Organic farmers in the southeastern US face a variety of management challenges in restoring soils to sustained productivity. The results from this study suggest that a suite of techniques, when used in concert, have the potential to restore soil C and other aspects of agronomic soil quality. This work also demonstrates how systems-level studies can elucidate interactions between management practices (e.g., mulch and compost application) that could not have been predicted by studying techniques individually. This unexpected interaction between residue quantity and compost application has agronomic implications, as non-mulched treatments required additional weeding labor. These results of this study indicate that organic, conservation tillage systems may provide farmers on degraded southeastern US soils low-input, organic alternatives that can restore soil C and keep lands in cultivation.

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Estimating organic premiums in the US fluid milk market

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Abstract

Using actual retail purchases from the 2006 Nielsen Homescan panel data, we estimate a hedonic model on price premiums and discounts associated with household characteristics, market factors, and product attributes focusing on the organic attribute for fluid milk. The organic attribute carries a significant price premium, which is largest of all product attributes considered in this study. Further, additional price variations among organic milk are observed for differences in fat content, container size and branding. Specifically, the results suggest that organic price premiums for half-gallon milk range from $1.23 for whole private label organic milk (60–68% above conventional counterpart) to $1.86 for nonfat/skim-branded organic milk (89–109% above conventional counterpart). The study also found that milk sold in a discount store (i.e., supercenter or club warehouse) was price 13 cents per half gallon, or 7.4%, below milk sold through other venues, and that milk on sale was priced 26 cents per half gallon, or 14.3%, less than the regular average price. Although household characteristics exert little influence on price relative to product attributes and market factors, the study does find that unmarried households and those with children under six pay slightly higher prices for milk, possibly due to time constraints.

Key words: organic milk, hedonic price, market factors, product attributes, branding, Nielsen Homescan, organic premium

Introduction

Spurred by concerns over personal health and nutrition, consumer interest in organic foods has grown rapidly over the past decade. In fact, the US organic food industry grew from just over $1 billion in sales in 1990 to $18.9 billion in 2007 representing 3.3% of total food sales[1,2]. Consumers generally cite credence characteristics, such as health and environmental concerns, as a primary motivation for organic usage[3,4]. Credence attributes bundled with commodity specific characteristics, such as taste and freshness, create a market premium for organic foods. Consumer awareness and knowledge about organic food and related attributes impact consumers' attitudes and their willingness to pay a premium. However, complete awareness and knowledge about organic foods does not necessarily mean a consumer will purchase the food, due to other barriers such as price or skepticism of perceived attributes[3,4].

An important factor affecting the decision to purchase organic foods is the price premium that consumers must pay for attributes associated with organics and the additional costs of producing organic foods, such as increased input costs, certification costs and lowered yields. High price premiums not only discourage nonusers from entering the organic market, but also keep current users from purchasing more organics. On the other hand, high price premiums may encourage production of organic foods. Therefore, the organic premium is an important market signal, which balances the demand and supply conditions of the organic sector.

Traditionally, studies of organic foods have measured consumers' attitudes and willingness to pay an organic price premium through the contingent valuation method rather than using actual purchase choices. A comprehensive review of literature on consumer perceptions and preferences of organic foods by Yiridoe et al.[4] suggested that caution should be exercised when drawing any conclusions from earlier studies with such limited short-term time-series data on willingness to pay a price premium. Although findings from the literature confirm that organic foods command a price premium[5–11], discrepancies in the magnitude vary across products and location. For example, using survey data, Wolf[5] found that 30% of respondents in California were willing to pay a 50% premium for organically grown

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grapes, whereas O'Donovan and McCarthy[6] found that about 70% of Irish consumers were not willing to pay more than a 10% premium for organic meat. Thompson and Kidwell[7] reported price premiums for organic produce in Arizona ranging from 40 to 175% depending on the type of produce. A focus group discussion of Australian consumers observed that most participants agreed that a price premium for organic food over nonorganic food was justified, but most of them did not know how much[12].

According to the Nutrition Business Journal (NBJ)[2], of the top five selling organic food categories in 2007, dairy products were second only to fruits and vegetables (16% for dairy and 37% for fruits and vegetables combined). In 2007, organic milk and cream made up 52% of the $3.1 billion US organic dairy market[2]. According to SPINS, a market research and consulting firm for the natural products industry, dollar sales of organic milk for the 52-week period ending November 3, 2007 increased for gallons, half gallons and quarts by 13.5, 13.2 and 12.2%, respectively[13]. Likewise, Nielsen LabelTrends found that unit volume for refrigerated organic milk grew 18.5% for the 52-week period ending October 6, 2007[13].

The focus of this study is a vital part of the organic dairy market: organic fluid milk, excluding buttermilk and flavored milk. Few empirical studies have investigated the organic price premiums consumers are paying in the market-place when they have a choice between organic and conventional fluid milk (e.g., see Glaser and Thompson[8] and Kiesel and Villas-Bois[14]). The objective of the study is to estimate price premiums and discounts associated with household characteristics, market factors and product attributes, focusing on the organic attribute for fluid milk using actual retail purchases from the 2006 Nielsen[15] Homescan panel data.

Data Source

The Homescan panelists constitute a random sample that is representative of the US population and provides purchase information of food items for at-home consumption. Each household is supplied with a scanner device that the panelist uses at home to record grocery items purchased at all retail outlets, ranging from grocery stores, supermarkets, supercenters and club warehouses to natural food and specialty stores, and consumer cooperatives. The household either scans the Uniform Product Code (UPC) or a designated code for random-weight purchases for each food item. Each purchase records the date, the quantity purchased, expenditure for that quantity, promotional information including whether or not the item is on sale, and detailed product characteristics. The focus of this study is to analyze milk purchases with an emphasis on the organic attribute.

Total enrollment in the Homescan panel for 2006 was over 37,000 households, but to avoid would-be data problems resulting from incomplete reporting, only those households that reported purchases for at least 10 months were included. Panelists do not explicitly report prices; they report the total expenditure and the quantity of milk purchased. Prices for organic and conventional milk are derived as unit values—the ratio of reported expenditures, net of any promotional and sale discounts, to the reported quantities for each purchase record. In order to avoid potential problems stemming from inadvertent reporting errors, derived unit values greater than the sample mean plus three standard deviations are considered outliers and thus excluded from the sample.

Each purchase record is identified by type (organic, lactose-free or conventional), fat content (nonfat/skim, low-fat, whole or unknown), container size (quart, half gallon, gallon or other), and branding (branded or private label). To categorize milk by fat content, classifications as defined by the US Food and Drug Administration are used[16]. 'Nonfat/skim' milk has less than 0.5 g of milk fat per cup, 'low-fat' milk has less than 4.7 g of milk fat per cup, and 'whole' milk has 8 g of fat per cup[16]. The definition of 'low-fat' includes milk labeled as 0.5 to 2% and reduced/low-fat. Purchases recorded as 'other' container sizes or 'unknown' fat contents are excluded from the analysis (making up 1.6% of total records). Table 1 provides a list of variables constructed from the data to be used in the empirical estimation.

Table 2 shows the percentage of purchases across product characteristics for conventional and organic milk. Low-fat milk makes up the largest proportion of both conventional (54.1%) and organic (48.3%) milk purchases. The percentage of whole milk purchases is about the same for conventional (22%) and organic (21.6%) milk. Organic nonfat/skim milk is bought proportionally more often (30.1%) than conventional nonfat/skim milk (23.9%). However, purchase differences among container sizes across conventional and organic milk are more evident. Conventional milk is bought in gallon containers most frequently (62.9%) and the bulk of organic milk is purchased in half-gallon containers (87.8%). Purchases of organic milk in quarts are rare, making up only 1.8% of total organic purchases, whereas conventional quarts are bought 5.8% of the time. Likewise, gallon purchases of organic milk are also low (10.4%). The findings across container size are not surprising. Other studies have also found that organic milk is largely available only in half gallon containers[8,17], whereas conventional milk is sold in a variety of container sizes. Percent of private label sales for organic milk were noticeably lower (27.1%) than conventional milk (68.1%) in 2006. Dimitri and Venezia[18] found that in 2004 only 10% of organic milk was purchased under a private label, underlining the inroads private labels are making in the organic industry[2].

Methodology

A limitation of the neoclassical theory of consumer demand is its inability to explain why consumers derive utility from commodities as well as its inability to predict demand for

Table 1. Variables included in the hedonic model, 2006.

Variable	Definition
Dependent variable	
Price	= unit value of milk (expenditure net of any promotions divided by the corresponding quantity), cents per ounce
Independent variables	
HOUSEHOLD CHARACTERISTICS	
Income	= the ratio of household income over the federal poverty level, where household income is the midpoint of the income class
Married (employed)	= 1 if household's marital status is married and both spouses are employed, = 0 otherwise
Married (at-home)	= 1 if household's marital status is married and only one spouse is employed, = 0 otherwise
Single[1]	= 1 if household's marital status is single, = 0 otherwise
Child under six	= 1 if a child under six years old is present, = 0 otherwise
Education	= 1 if household head has a specific education (high school diploma or less, some college, college degree or beyond[1]), = 0 otherwise
Age	= 1 if household head's age is in a specific group (< 40, 40–64, 65 or older[1]), = 0 otherwise
Race/Ethnicity	= 1 if the household head is a particular race/ethnicity (African-, Hispanic-, Asian-, other-American, white[1]), = 0 otherwise
MARKET FACTORS	
Discount	= 1 if purchase made in a superstore or club warehouse, = 0 otherwise
Sale	= 1 if purchase made on sale or under promotion, = 0 otherwise
Season	= 1 if purchase made in a specific season (Spring, Summer, Fall, Winter[1]), = 0 otherwise
Region	= 1 if the household resides in a specific region (Northeast, Central, West, South[1]), = 0 otherwise
Urban	= 1 if the household resides in an urban area
PRODUCT ATTRIBUTES	
Conventional brand	= 1 if conventional milk is purchased under a brand name, = 0 otherwise
Organic brand	= 1 if organic milk is purchased under a brand name, = 0 otherwise
Private label[1]	= 1 if purchase made under a private label, = 0 otherwise
Organic	= 1 if organic milk, = 0 otherwise
Container size	= 1 if purchase made in a specific container size (quart, gallon, half gallon[1]), = 0 otherwise
Fat content	= 1 if purchase made in a specific fat content (low-fat, whole, nonfat/skim[1]), = 0 otherwise
Lactose-free	= 1 if lactose-free milk, = 0 otherwise

[1] Reference category.
Source: Nielson Homescan Data, 2006.

Table 2. Percent of purchases by product characteristics, 2006.

Characteristic	Conventional	Organic
	---------- Percent ----------	
Skim	23.91	30.12
Low-fat	54.07	48.26
Whole	22.01	21.64
Quart	5.81	1.79
Half gallon	31.32	87.82
Gallon	62.87	10.39
Private label	68.12	27.13
Branded	31.88	72.87
Number of observations	986,530	19,994

Source: Nielsen Homescan, 2006.

new products. Realizing the weaknesses of the neoclassical approach, Lancaster[19] proposed the characteristics theory to address some of the inherent limitations found in the neoclassical demand theory. The characteristics theory assumes that consumers derive utility from the characteristics or attributes inherent in a good or service. It is the intrinsic properties of a particular good that make it different from other goods that, in some instances, may be quite similar. The model developed by Lancaster[19] makes several modest assumptions. It is not the good itself that gives rise in utility to the consumer, but the characteristics within the good. In general, it is assumed that a good possess more than one characteristic and that many characteristics will be shared by more than one good. And finally, goods in combination may create characteristics completely different than those pertaining to the goods separately.

Agricultural economists have expanded Lancaster's[19] theory to develop hedonic approaches that model price as a function of quality attributes to estimate the implicit values of product characteristics[20–22]. Hedonic modeling relies on the assumption that the price of a product must be low enough relative to the prices of other products to be represented on the efficiency frontier[19]. The theory states that the price of a product is a function of all its associated attributes z,

$$p(z) = (z_1, z_2, \ldots, z_n),$$

so that the marginal implicit values of the product's attributes sum up to the price paid by the consumer[20]. The

amount of attributes demanded by the consumer must be met by the amount supplied by the producer[21]. This implies that both consumers and producers distinguish product attributes approximately the same way and that the decisions made by each group leads to an equilibrium condition that neither consumers nor suppliers have any incentive to change[9].

Given the nature of Homescan data that may contain multiple observations from the same household, the error terms are likely clustered-correlated and not independently distributed. Thus, the covariance estimates obtained from applying the standard ordinary least squares estimation are likely biased, which would yield inappropriate standard errors and misleading tests of statistical significance[23]. The error terms in the hedonic price equation are assumed to be cluster-correlated. To estimate the hedonic equation, the Stata[24] program's family of commands designed for survey data is used, which performs the regression procedure via the weighted least squares for survey data. Therefore, the price of milk, P_i, in the hedonic model is specified as

$$P_{it} = \alpha_0 + \sum_{n=1}^{16} \alpha_n SOC_{nit} + \sum_{r=1}^{11} \beta_r MKT_{rit} + \sum_{s=1}^{10} \gamma_s PRO_{sit} + \delta_1 ORG_{it} + \sum_{v=2}^{8} \delta_v ORG_{it} * PRO_{vit} + e_{it},$$

where P_{it} is the price of milk paid by the ith household in time t; SOC_{it} represents a household's socio-demographic characteristics; MKT_{it} represents a set of market factors such as type of store, on sale occasion, season, region and location (urban) of purchase; PRO_{it} represents product attributes such as container size, fat content, branding and the lactose-free attribute; ORG_{it} represents the organic attribute of milk, and e_{it} is the error term. Interactive terms between organic purchases and selected product attributes are included to allow for price differentiation among the two types of milk.

The hedonic price model represents a reduced-form equation reflecting both the supply and demand influences simultaneously. Unfortunately, there is no rule-of-thumb for choosing the appropriate functional form *a priori* in regression analysis. Thus, the choice of the functional form remains an empirical issue. Due to its ease of interpretation and previous application to hedonic pricing structures for organic foods[10,11,14], the linear functional form is chosen.

Table 3. Hedonic price results of fluid milk, 2006.

Variable	Coefficient	Standard error
Constant	2.962***	0.032
Household characteristics		
Income	0.015***	0.002
Married (employed)	−0.024***	0.010
Married (at-home)	−0.044***	0.009
Child under six	0.026*	0.014
High school diploma or less	0.007	0.017
Some college	0.006	0.011
Age < 40	0.040***	0.013
Age 40–64	0.014*	0.007
African-American	0.040***	0.013
Hispanic-American	0.008	0.015
Asian-American	−0.009	0.024
Other-American	0.019	0.026
Market factors		
Discount	−0.196***	0.017
Sale	−0.398***	0.013
Spring	0.029***	0.004
Summer	−0.029***	0.004
Fall	−0.031***	0.003
Northeast	−0.434***	0.041
Central	−0.448***	0.022
West	−0.273***	0.029
Urban	−0.005	0.017
Product attributes		
Lactose-free	1.987***	0.053
Quart	1.123***	0.040
Gallon	−0.694***	0.019
Low-fat	0.065***	0.008
Whole	0.153***	0.010
Conventional brand	0.257***	0.019
Organic brand	0.819***	0.046
Organic	2.091***	0.057
Organic × Lactose-free	−1.477***	0.119
Organic × Quart	0.265***	0.090
Organic × Gallon	−0.527***	0.072
Organic × Low-fat	−0.147***	0.045
Organic × Whole	−0.173***	0.044
Number of observations	1,006,524	
R^2	0.678	

Source: Nielson Homescan Data, 2006.
Note: *** and * indicate the estimated coefficients are significantly different from zero at least at the 1 and 10% significance level, respectively.

Results

As shown in Table 3, the R-squared, a measure of goodness-of-fit, is 0.678 implying that about 68% of the variation in price is explained by the independent variables. Given that cross-sectional data are used, the reported R-squared is quite high and is deemed satisfactory. The coefficients represent a change in price (cents/ounce) relative to the reference group (conventional, private label, half gallon, nonfat/skim milk, purchased in the winter, in a southern rural area, not on sale or sold in a discount store). Overall, the estimated coefficients appear to be reasonable in magnitude and satisfactory in terms of statistical significance.

From Table 3, we can see the household characteristics exert less influence on the price of milk in terms of both statistical significance and magnitude relative to market factors and product attributes. However, some interesting findings do appear. For example, higher-income households had a higher willingness to pay for milk, possibly due to the

correlation between income status and the quality of shopping venue and product offering. Our finding is consistent with Thompson and Kidwell[7], who found that higher household income increases the probability that a household will choose to shop at a specialty grocery store, which tends to maintain higher prices on average.

We also found that married households tended to pay less for milk, particularly those that have an unemployed spouse at home, compared with single households. Likewise, households with a child under six paid slightly more than those without. Kiesel and Villa-Boas[14] suggested that single mother households and households with children under the age of six have higher opportunity costs of time, and are therefore more likely to benefit from informational effects of USDA labeled organic milk. Similarly, Wier et al.[25] concluded that households with children under six, rather than households with children in general, are more likely to purchase organic foods.

With regard to the remaining household characteristics, we found no significant relationship between educational attainment and the price paid for fluid milk. Likewise, only African–Americans were found to pay a significantly higher price than other races/ethnicities. Age of the household head was negatively correlated to willingness to pay for milk—younger households paid more than older households.

All market factors are significantly different from zero at the 1% significance level, with the exception of 'Urban'. As expected, milk sold at a discount store or on sale was priced significantly lower. Milk sold at a discount store (i.e., supercenter or club warehouse) was priced 0.20 ¢/oz. (13 cents per half gallon) less than milk sold through other venues, such as a grocery store, equivalent to a 7.4% price differential. Specialty chain grocery stores are recorded in the same category as all other grocery stores in Homescan. Moreover, milk on sale was discounted 0.40 ¢/oz. (26 cents per half gallon), or 14.3% below the average regular price.

Dairy farmers in the US are paid a relatively uniform price under Federal Milk Marketing Orders according to their marketing area[26]. Federal Milk Marketing Orders insure a minimum price calculated on a monthly basis that the buyer, or handler, must pay the dairy farmer. To control for these monthly price variations across marketing areas, seasonal and regional variables are included in the model. Average monthly prices given to dairy farmers in dollars per hundredweight reflect the estimated seasonal and regional variation in 2006[27].

As anticipated, prices vary by season in a regular and cyclical way, representing the smallest variation among all market factors. Estimated prices of milk in the spring were 0.03 ¢/oz. more than those in the winter, but were 0.03 ¢/oz. less in the summer and fall. Estimated results for regional prices are consistent with previous research[28], in which milk prices are significantly higher in the south as compared with the rest of the US and at their lowest in the central region. Leibtag[28] found that consumers in rural areas pay lower average prices for milk than those in urban areas, but we found no significant price difference. A possibility is that urban consumers purchase milk in smaller containers, whereas rural consumers may purchase milk in larger containers, thus leading to lower calculated average prices. However, our model controls for other factors such as container size, resulting in insignificant price differences between urban and rural households.

Product attributes such as the lactose-free attribute, container size and fat content all significantly affect the price of milk. As expected, consumers paid a large premium of about 2 ¢/oz. for lactose-free milk, due to the increased manufacturing costs of removing lactose. As with most goods, purchasing products in bulk packaging, or in this case—larger container size, carries a price discount. In contrast, the price of milk increases with fat content. Both the price of low-fat and whole milk was more than that of nonfat/skim milk, 0.07 and 0.15 ¢/oz., respectively. This is because milk fat, or butterfat, has a market value so that consumers have to pay a premium for the increased fat content.

Not surprisingly, the price of branded conventional and organic milk carried a premium over private label milk. However, differences in magnitude between the two types of milk appear. For example, branded conventional milk carried a premium of 0.26 ¢/oz. (about 15% above conventional private label half gallons), whereas branded organic milk carried a premium of 0.82 ¢/oz (about 26% above organic private label half gallons). In addition to the premiums associated with branded organic milk, the organic attribute itself carried the largest and significant price premium of 2.09 ¢/oz. The results suggest that consumers purchasing organic milk are willing to not only pay the large organic premium but also pay a larger 'brand' premium for organic versus conventional. The larger 'brand' premium for organic milk implies that consumers place a higher value on branded organic milk compared with branded conventional milk over their private label counterparts. Grebitus et al.[17] found that milk consumers in Germany were influenced by the brand of organic milk more so than the brand of conventional milk, leading them to believe that consumers may use certain brands as a cue for the credence attribute 'organic'.

By allowing the organic attribute to interact with the lactose-free attribute, fat content and container size in our hedonic model, additional changes in price corresponding to each product attribute can be tested. The estimated negative coefficient for organic lactose-free milk (Organic × Lactose-free) suggests that when the organic and lactose-free attributes are packaged together, the bundled premium is smaller than the sum of the two individual premiums. This may be due to the fact that consumers are already paying a large organic premium and may not be willing to pay an additional high premium for the lactose-free attribute. Additionally, the organic milk industry, through economies of scale, may be attempting to capture more sales by offering the lactose-free attribute at a much lower marginal price premium than when sold as

Table 4. Average half-gallon prices and associated premiums in dollars per half gallon, 2006.

	Conventional		Organic	
Fat content	**Private label**	**Branded**	**Private label**	**Branded**
	Average prices			
Nonfat/Skim	1.71	2.10	3.16	3.65
Low-fat	1.73	2.01	3.03	3.59
Whole	1.81	2.04	3.15	3.55
	Premiums			
Nonfat/Skim			1.34	1.86
Low-fat			1.24	1.77
Whole			1.23	1.75

Note: All prices are in dollars per half gallon. Average prices were constructed using the Nielsen projection factor. Premiums are calculated using estimated coefficients from Table 3 and inflated by 64 ounces.
Source: Nielsen Homescan, 2006.

nonorganic. Nevertheless, lactose-free carries a price premium among organic milk.

As indicated in Table 3, the container size of organic milk further affected price. Price premiums and discounts associated with container size were 'stretched' or 'inflated' when sold as organic. For example, organic milk sold in quarts had an additional price premium of 0.27 ¢/oz. equating to a total price premium of 1.39 ¢/oz. above that of a half gallon. However, the opposite was true for organic milk sold in gallons, in which the total price discount equated to 1.22 ¢/oz. relative to an organic half gallon. Because organic milk carries such a high price premium due to additional production costs, we would expect the price premiums and discounts related to container size to be inflated per ounce.

Additional changes in price for organic milk associated with fat contents were also found. Contrary to the findings for conventional low-fat milk (0.07 ¢/oz. premium above conventional nonfat/skim), the negative coefficient for the interactive term between organic and low-fat (Organic × Low-fat) suggested that organic low-fat milk had a price discount of 0.08 ¢/oz. compared with organic skim/nonfat milk. Similar findings were also found for organic whole milk (0.02 ¢/oz. price discount over organic nonfat/skim). It is plausible that households pay the highest premium for nonfat organic milk because consumers with concerns about individual health and nutrition have been found to be more likely to purchase organic foods[29,30]. The presence of butterfat in low-fat and whole milk may be viewed by the organic milk consumer as an unhealthy food choice, and thus, they are willing to pay an additional premium for the nonfat product.

Because organic milk is predominantly sold in half gallons and such stark differences emerge between conventional and organic branding, the remainder of the discussion focuses on these types of milk. Table 4 presents average half-gallon prices and organic premiums in terms of dollars per half gallon. Holding household characteristics

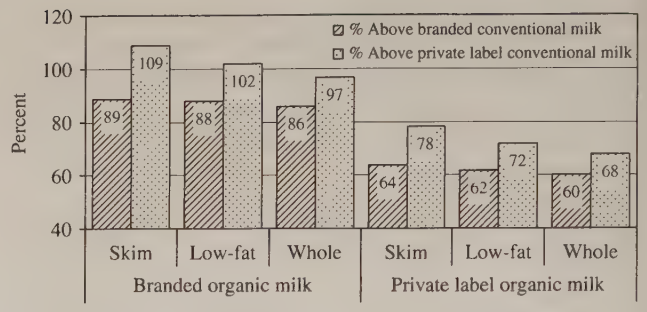

Figure 1. Price premiums: half gallon of organic milk. Note: premiums reflect the percent above their respective average actual half gallon conventional milk prices within each fat content category found in Table 4. Source: Nielsen Homescan, 2006.

and market factors constant, the organic premium in absolute value is calculated by adding the relevant estimated coefficients for organic milk found in Table 3. For example, the organic premium for a half gallon of branded low-fat milk is 2.76 ¢/oz., or $1.77 per half gallon. Previous studies using the contingent valuation approach typically report organic price premiums as a percent above conventional prices instead of absolute dollars and cents, in order for respondents to report their willingness to pay for organic food in relative terms. To be consistent with the literature for comparison, the premiums as a percentage above the average actual prices of conventional milk found in Table 4 are reported in Figure 1. Therefore, the $1.77 per half-gallon premium is about 88% above the average price paid for its conventional branded counterpart and about 102% above its conventional private label counterpart.

The results depicted in Figure 1 clearly indicate the price differences in branded and private label organic milk. The premiums for branded organic milk range from 86 to 109% above conventional prices and are wholly above the premiums for private label organic milk, which range from 60 to 78%. Previous studies on the determinants of milk consumption have found that consumers are habitual in their milk purchasing patterns and are reluctant to shift from their usual type of milk in terms of fat content[31,32]. Therefore, Figure 1 can be thought of as a representation of premiums paid by consumers switching from conventional to organic within their preferred fat content category. However, our estimated organic premiums on milk seem much higher than those reported on fresh fruits and vegetables. Lin et al.[10] estimated that price premiums for organic produce vary from 20% for grapes to 42% for strawberries and from 15% for carrots and tomatoes to 60% for potatoes. The high premium on organic milk relative to organic produce is to be expected because it reflects not only the higher cost of organic feed but also the costs of a more labor-intensive production process.

The estimated organic premiums for milk found in this study are slightly higher than that of Glaser and Thompson's[8] study, but seem in agreement with that of Dhar and Foltz's[33] study that showed the price differences between organic and unlabeled milk averaged about $3.00

per gallon, or about 123% above unlabeled milk, from 1997 to 2002. Glaser and Thompson[8] found that a half gallon of organic milk was priced between 66 and 72% above conventional private label milk and between 50 and 63% above conventional branded milk. The lower estimated premiums of Glaser and Thompson[8] may be linked to their data source that is limited to supermarket chains from November 1996 to December 1999. Considering the fact that 67% of organic sales in 1998 occurred in natural food stores[34] which typically command higher prices than supermarkets, they could have very well underestimated the premiums. Estimated organic premiums presented in this study may give a more accurate representation of purchases being made in the current milk market as they represent all retail markets.

Conclusions

This study estimated a hedonic pricing model to investigate price premiums and discounts associated with household characteristics, market factors and product attributes for fluid milk. Most notably, the organic attribute carried a large and significant premium. Furthermore, additional price variation associated with container size and fat content occurred for organic milk over its conventional counterpart. Estimated organic premiums across fat contents and branding for half gallon milk ranged from about 60 to 109% above their respective conventional prices. On the supply side, a larger premium for organic milk relative to other organic foods, such as fresh produce, is reasonable and can be justified since organic milk requires higher production costs. On the demand side, consumers are willing to pay such large premiums for organic milk because of perceived health and environmental benefits from organically produced foods, as well as other quality attributes, such as freshness and taste[3,4]. These attributes demanded by the consumer must be supplied by the producer in such a way that the decisions made by each group leads to an equilibrium condition[9,21].

Milk free of the genetically engineered hormone somatotropin (known as rBGH- or rBST-free milk) has been demanded by some consumers, especially, those who are health conscious. Organic milk is also free of genetically modified ingredients, as well as other attributes such as being pesticide and antibiotic free. Previous studies have found that rBST-free labeled milk affects consumption of organic milk and such labels also carried a premium[14,33]. However, the Homescan data do not code for rBST-free labeled milk. To identify rBST-free milk, Kiesel and Villa-Boas[14] linked the Homescan data to secondary data sources that provide rBST-free labeling information at the brand level. Dhar and Foltz[33], on the other hand, used the Information Resources Inc (IRI) supermarket scanner data to identify brands of milk labeled as rBST-free and organic through interviews with processors and retailers. Moreover, previous studies have found that other product characteristics not available in the Homescan data, such as freshness, taste and quality, significantly affect purchases of milk[31,32]. It would be of interest for future research to link these additional consumer preferences to actual purchase data.

Given the relatively low availability of organic milk in a variety of container sizes, it might be of interest for organic milk suppliers to consider giving the consumer more container size options. Studies have shown that organic milk is a 'gateway food' and is one of the first organic foods that consumers purchase before entering the organic food realm[35]. By increasing purchases of organic milk, it may bolster the organic food industry as a whole.

Additionally, studies have shown that some consumers may use certain brands of organic milk as a cue for the organic credence attribute[17]. However, as the organic market continues to mature and consumers become more familiar with other cues, such as the USDA organic seal, the market potential for organic private labels increases. The large price premium between private label and branded organically produced milk could help local venues and retailers capture some of the booming organic trend. In fact, private label sales of organic milk are already eating away at sales of branded organic milk. In 2004 according to Nielsen[15] Homescan data, private labels made up just 10% of all organic milk purchases, while two major brands of organic milk made up 80%[18]. However, the results of Nielsen's[15] 2006 data show that the percentage of private label purchases has increased to over 27%. In contrast, private label sales of conventional milk have increased only slightly from 64% of purchases in 2004[18] to just over 68% in 2006. This market growth is consistent with our finding that organic premiums are higher for branded milk than for private label milk.

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Is there a promising market 'in between' organic and conventional food? Analysis of consumer preferences

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Abstract

Various products incorporating single aspects of organic production systems such as lower inputs of pesticides, food additives or concentrated animal feed are found on the food market (referred to as low-input products hereafter). In our study, we analyzed how consumers react to low-input products in a purchase simulation with certified organic, conventional and low-input products. In the purchase simulations, each participant was asked to make three consecutive purchase decisions, one each for milk, yogurt and apples. The results of a cluster analysis revealed one cluster with a high preference for organic products and three clusters that featured considerable shares of low-input purchases. The latter clusters, however, were not characterized by a clear preference for low-input products. Rather, they bought mixed baskets of goods, i.e., low-input products in combination with either organic or conventional products. The low-input products in the categories milk, yogurt and apples did thus not necessarily attract the same groups of people. Interestingly, we found that most consumers who chose low-input products in the simulations usually buy those particular products in conventional quality. We conclude that in our study, we found a heterogeneous group of low-input buyers. For the organic sector, communicating the various aspects of organic production might be a promising strategy for gaining new customers. The low-input products in the purchase simulation only featured one special attribute, whereas organic products incorporate several.

Key words: buying simulation, consumer preferences, organic food, low-input food

Introduction

The European market for organic food is the biggest market for organic food worldwide. The market volume in 2006 was estimated to be between 13 and 14 billion Euros with a growth rate of approximately 10% compared to 2005[1]. Within Europe, the German organic market is by far the largest with an annual turnover of 5.3 billion Euros in 2007 and a growth rate of 15% compared to the previous year[2]. Recent studies suggest that 91% of all German households consume organic food products[3]. In Germany, certified organic products are widely available in regular supermarkets as well as in organic food stores, in drugstores and at farmers' markets.

Most organic products sold in Germany carry the well-known governmental organic label ('Bio-Siegel'), which indicates compliance with the EU Regulation (EEC) No. 2092/91[4]. In addition, the German organic market is characterized by a relatively large number of private organic certification standards that exceed the EU Regulation (e.g., Demeter, Bioland and Naturland). Consequently, a variety of organic labels and standards can be found on food products, with many products carrying both the governmental as well as a private organic label together with a company's brand. In this respect, the German organic market is unique compared to other European countries. In addition to certified organic products, other kinds of products are found on the food market: conventional producers increasingly launch products incorporating single aspects of organic production systems, such as lower inputs of pesticides, food additives or concentrated animal feed. These products do not comply with organic standards and are referred to as low-input products in this paper. While there are many examples of low-input products (e.g. free-range eggs, the products by the British company 'innocent', the yogurt line 'Natur rein' by the German company 'Bauer'), the authors do not know of any published data on the market share and growth rate of low-input products.

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Previous studies from Germany on consumer preferences regarding product attributes indicate that consumers rate the overall system of organic farming as less important than individual aspects incorporated in the system, such as animal welfare and the abandonment of the use of GM technologies, pesticides and antibiotics[5,6]. Studies from other European countries moreover suggest that consumers are not well informed about organic production and how certification works[7–9]. A scientific study on consumer perception of low-input products revealed a similar picture[10]: While consumers expressed great interest in pasture-raised livestock products, it also turned out that many consumers believed, almost certainly erroneously, that they had already bought such products. Overall, previous studies thus indicate that consumers seem to lack knowledge about organic standards and farming practices in general[5–10].

Numerous studies have been conducted on consumer preferences for organic food[8]. However, it remains unclear how the organic sector is affected by the emerging competition imposed by low-input products. The present study was designed and conducted to analyze how consumers perceive low-input products that are otherwise produced in a conventional way. By means of purchase simulations with subsequent personal interviews, we investigated how consumers react to low-input products in relation to certified organic and conventional products. In this paper, we identify whether low-input products substitute organic or conventional products, and determine whether low-input represents an 'intermediate choice'. In order to identify factors that influence consumer preferences regarding organic, low-input and conventional food, the participants are grouped into four consumer segments according to their buying behavior by means of a cluster analysis. The consumer segments are then characterized in terms of product preferences, attitudes toward food quality and safety and socio-demographic variables.

Methods

Our study combined two methods of data collection. The buying behavior of consumers was surveyed by purchase simulations. In subsequent face-to-face interviews, factors that influence the product choice were investigated. A cluster analysis was conducted to identify groups of participants with similar buying patterns. The following sections describe the methods of data collection and the survey design as well as the procedure of data collection and the method of data analysis.

Survey design

In our study, purchase simulations were conducted to analyze consumers' choices between certified organic, low-input and conventional products. The design of the purchase simulations resembled the method of data collection that is used in consumer choice experiments. However, we focused on creating a realistic buying situation in the purchase simulations. While in many studies with choice experiments, the participants are presented with pictures or descriptions of products and are required to make repeated choices in the same product category (e.g., see the studies by Lusk and Schroeder[11], Lockshin et al.[12], Mtimet and Albisu[13], Loureiro and Umberger[14], Barreiro-Hurlé et al.[15], Enneking[16], Hu et al.[17]), we used three-dimensional products and the participants only made one purchase decision per product category. The product categories investigated in our study were milk, yogurt and apples. These product categories were chosen in order to investigate the buying behavior for both animal and plant products as well as processed and unprocessed food products. Each participant was asked to make three consecutive purchase decisions, one each for milk, yogurt and apples. In each product category, the choice set contained three different product alternatives: conventional, low-input and organic. In addition, the no-choice option was offered. The organic alternatives were labeled with the German governmental organic logo ('Bio-Siegel'). The low-input products were labeled with respective product information, which is shown in Table 1. The choice sets regarding milk and yogurt comprised product packages that were created by a design company for the purpose of this study. The packages contained all relevant product information but no brand name. All apples in one choice set came from the same delivery so that they looked similar. The product prices were displayed on laminated price tags. To avoid a hypothetical bias, the participants had to pay for the chosen products.

Table 1. Low-input products tested in the purchase simulations.

	Product claim
Milk	From pasture-raised cows
Yogurt	Free from artificial additives and flavors
Apples	With reduced use of pesticides

Across the sample, the price levels of the products varied. In total, four different combinations of prices were tested. Among the three competing product alternatives, the conventional products were always the cheapest and the organic the most expensive. The low-input products were offered at in-between price levels and were either priced right in the middle between the two others or closer to the organic products. The actual prices for the conventional and the organic alternatives were selected on the basis of market prices in autumn 2007 when the study was carried out.

After the purchase simulations, face-to-face interviews based on a standardized highly structured questionnaire were conducted to shed light on factors influencing the buying behavior. First, all participants were asked which of the two remaining alternatives they would have chosen if the preferred product had not been available. Secondly, attitudes toward food quality and safety were explored by 18 Likert-scaled statements. This section was included in

Table 2. Excerpt from the screening questionnaire.

'How often did you buy [the product group] in organic quality during the last month: never, once or twice, or more than twice?'[1]

	Buying frequency		
Product groups	**Never**	**Once or twice per month**	**More than twice per month**
Vegetables	0	1	2
Fruits	0	1	2
Meat	0	1	2
Eggs	0	1	2
Milk and dairy products	0	1	2
Bread and cereal products	0	1	2
Beverages	0	1	2

[1] The recruiters repeated this question for each product group listed in the table and marked the respective answer. Afterwards, the recruiters calculated the total score by summing up the points of the answers.

the questionnaire since previous research showed that consumer attitudes toward topics such as health, nutrition, protection of the environment and lifestyle influence the propensity of organic food consumption (e.g., see Hughner et al.[8], Zanoli and Naspetti[18], Loureiro et al.[19], Wier et al.[20], Hill and Lynchehaun[21]). Thirdly, the participants were asked in an open-ended question which kind of milk, yogurt and apples (conventional or organic) they usually buy. Finally, socio-demographic variables were recorded.

The target group for this study were occasional consumers of organic food. These consumers purchase both, conventional as well as organic food, and are thus not fully committed to either of the two, which is why this consumer group was chosen for this study. To identify occasional consumers, a standardized screening questionnaire was used. The questionnaire included an organic index that was based on the buying frequency of organic products in several product groups (see Table 2). People with an organic index between two and nine points (out of a maximum of 14 points) were considered occasional buyers. In this context, we would like to point out that even though non- and fully committed buyers were excluded, there is still a considerable range of organic consumption propensities among the participants of the study.

Data collection

The survey was conducted in three cities in central Germany in October and November 2007. The purchasing power of the three administrative districts (99.6, 94.0 and 90.8, respectively) is relatively close to the German average (100.0)[22]. The participants for the purchase simulations were recruited based on quota sampling for age and gender using a standardized screening questionnaire. The recruiters approached people in public places like shopping malls, pedestrian areas and in front of supermarkets. People who fulfilled the screening criteria were asked to participate in the study and were given an appointment for the actual survey which, on average, took place two days later. The participants were informed that they would take part in a European study on consumers' preferences for food. No particular reference to low-input food was made. The purchase simulations and interviews were conducted in seminar rooms of the local universities or the YMCA, respectively. Upon arrival at the survey location, participants were given standardized information on the course of the survey. After the interviews, the participants were informed that the product packages in the purchase simulations had been designed for the purpose of the study.

Data analysis

Apart from uni- and bivariate analyses, a cluster analysis was conducted using SPSS 15.0 to detect groups of participants with similar buying patterns across the product categories. The term 'cluster analysis' covers different methods for grouping objects (e.g., persons) according to certain characteristics, aiming at identifying homogeneous subgroups of objects within a heterogeneous population[23]. In our study, the participants were grouped according to their buying behavior in the purchase simulations. An agglomerative hierarchical cluster analysis was used. The buying behavior was thereby measured by nine binary variables (three per product category). Six participants who had realized the 'no choice' option in one or more of the product categories were excluded from the sample as these cases determined outliers (reduced sample size $n = 143$). The remaining participants were then grouped with the average linkage (within groups) method using the Russel and Rao coefficient as proximity measure. A four-cluster solution was selected based on the elbow criterion and considerations of interpretation and manageability.

In order to identify factors that influence the buying behavior of consumers, the four clusters were analyzed based on information collected in the interviews. First, the clusters were compared regarding their attitudes toward food quality and safety. For each statement, the mean ratings of the clusters were compared by an analysis of variance (ANOVA). Secondly, the clusters were analyzed by means of ANOVA and two-sided Z-tests, respectively, regarding differences in socio-demographic variables.

Description of the sample

The socio-demographic make-up of the sample is summarized in Table 3. Altogether, the sample consisted of 149 participants of which 71.1% were female. The sample thus corresponded to previous empirical studies indicating that women are predominantly responsible for the food purchase in German households[24,25]. Two age groups were used in the quota sampling (18 to 44 and 45 to 75 years), and 49.7% of participants fell within the younger group.

Table 3. Summary statistics of the socio-demographic variables.

Variable	Description	Frequency	Mean	Standard deviation
Age	Age (in years)		42.51	14.82
	18 to 44	49.7%		
	45 to 75	50.3%		
Gender	1 if female	71.1%		
	0 if male	28.9%		
Education	No professional education	2.0%		
	High school degree and professional education	34.9%		
	College/University degree or higher	60.4%		
	Other	2.7%		
Children	1 if participant has children	49.0%		
	0 otherwise	51.0%		
Children $\leqslant$18 years	1 if participant has children $\leqslant$18 years	27.5%		
	0 otherwise	72.5%		
Number of children	Number of children that participant has	0 = 49.0%	0.93	1.22
		1 = 21.5%		
		2 = 16.1%		
		3 = 8.7%		
		$\geqslant$4 = 2.7%		
Age of children	Participants with children in the respective age groups[1]			
	Children up to 1 year	2.7%		
	Children 1 to 3 years	2.7%		
	Children 4 to 6 years	1.3%		
	Children 7 to 12 years	8.7%		
	Children 13 to 18 years	14.1%		
	Children older than 18 years	28.2%		
	No children	49.0%		
Household size	Number of members in the household	1 = 45.6%	1.94	1.16
		2 = 30.9%		
		3 = 14.1%		
		4 = 4.7%		
		5 = 2.7%		
		$\geqslant$6 = 2.0%		
Income	Monthly net household income in Euros			
	Less than 600	17.6%		
	600 up to below 1200	33.1%		
	1200 up to below 1800	22.3%		
	1800 up to below 2400	8.8%		
	2400 up to below 3000	7.4%		
	3000 up to below 3600	6.8%		
	3600 up to below 4200	2.0%		
	4200 or more	2.0%		

[1] Percentages add up to more than 100%, as multiple responses were possible.

This share was almost identical with the proportion of this age group within the German population between 18 and 75 years old[26]. The average age of the participants was 42 years. The level of education was relatively high in the sample with 60.4% of participants holding a university or college degree, whereas among the German population above 20 years of age, a share of only 12.5% was reported in 2007[26]. This could be ascribed to the target group of occasional organic consumers. Previous studies showed that, on average, consumers of organic food had a higher level of education than the rest of the population[27,28]. Single person households were overrepresented in the sample. They accounted for 45.6% of all households compared to 37.5% in Germany[26]. About a quarter of the participants had children up to 18 years, which corresponded to the German average[26]. Regarding the propensity of organic food consumption, a relatively high organic index was measured with a mean of 6.6 and a median of 7. More than half of the participants reached a high index of 7 to 9 points indicating that they were frequent buyers of organic food.

Table 4. Product alternatives bought in the purchase simulations.

Product alternatives	Milk		Yogurt		Apples	
	Frequency	%	Frequency	%	Frequency	%
Conventional	24	16.1	18	12.1	29	19.5
Low-input	35	23.5	44	29.5	22	14.8
Organic	88	59.1	83	55.7	97	65.1
No choice	2	1.3	4	2.7	1	0.7
Total	149	100.0	149	100.0	149	100.0

The remaining 47.0% were light to medium consumers with an index between 2 and 6 points.

Results

The actual choices made in the purchase simulations are presented in Table 4. The organic products were bought most frequently by more than half of the participants in all product categories. For milk and yogurt, the low-input products accounted for the second highest shares of purchases, whereas the conventional products had the lowest shares. Regarding apples, the order was switched: conventional apples were bought slightly more often than low-input apples.

Influence of price level on buying behavior

Across the sample, the product alternatives in the purchase simulations were offered at four different price levels. According to economic theory, the hypothesis to be tested was: the higher the relative price of an alternative, the lower the buying frequency. To determine whether an association existed between the price levels and the buying decision (organic, low-input or conventional), Chi-square tests of independence were applied. No significant associations could be detected (milk: $\chi^2 = 5.902$, df = 6, $P = 0.434$; yogurt: $\chi^2 = 7.114$, df = 6, $P = 0.310$; apples: $\chi^2 = 7.491$; df = 6, $P = 0.278$). The buying frequencies of the three alternatives were thus not influenced by the different relative prices. This result implies that price premiums close to those for organic products may be realized for low-input products.

Switch-over to low-input products

A comparison between the buying behavior in the purchase simulations and the stated *usual* buying behavior was used to analyze whether low-input products substituted organic or conventional products. The low-input alternatives were offered at higher prices than conventional products but were cheaper than the organic alternatives. Given that higher prices for organic food are referred to as the main purchase obstacle in the literature[8], it could be assumed that buyers of conventional products would not be willing to pay a price premium for low-input products. Buyers of organic products, in contrast, might be attracted by low-input products that are cheaper than organic yet offer one specific quality attribute. It was thus hypothesized that low-input products would primarily substitute organic products.

Interestingly, our results showed low-input products substituted conventional products to a much larger extent than organic products. Within the group of participants who stated that they usually buy the particular product in conventional quality, the share of people who chose the low-input alternative in the purchase simulations accounted for 31.1% for milk, 40.2% for yogurt and 27.3% for apples. Within the group of people usually buying the particular product in organic quality, the share of people who chose the low-input alternatives was significantly lower (based on two-sided *Z*-tests to compare column proportions) accounting for 13.6, 8.9 and 0.0% for milk, yogurt and apples, respectively. The conclusion can therefore be drawn that low-input products attracted people who usually buy the particular product in conventional quality.

Perception of low-input products as an intermediate choice

From the viewpoint of the production process, low-input products can be classified as an intermediate alternative between conventional and organic products. In our study, it was hypothesized that consumers share this view and perceive low-input as an intermediate alternative. To answer this question, the choices in the purchase simulations were compared with the stated 'alternative choice'. The alternative choice refers to the product that the participants would have chosen if the preferred product had not been available. In all three categories, the great majority of participants who chose the organic product in the purchase simulations ranked the low-input alternative second. This also applies to the conventional buyers. Irrespective of the product category at hand, the low-input product was thus seen as the most favorable second alternative by both conventional and organic buyers. The rankings of the low-input buyers revealed a rather diverse picture across the three categories. For milk, about two-thirds of the low-input buyers chose organic and one-third conventional as their second alternative. For apples, the opposite ranking was observed. Here, more than three-fourth of the low-input buyers ranked the conventional alternative second. Yet for

Table 5. Baskets of goods bought in the purchase simulations.

Number of products[1]	Frequencies in %[2]		
	Organic	Low-input	Conventional
0	14.8	50.3	66.4
1	21.5	34.2	22.1
2	32.9	12.8	8.7
3	30.9	2.7	2.7

[1] Number of organic, low-input and conventional products, respectively, in the 'baskets of goods'.
[2] Note that percentage values per column may not add to 100 due to rounding.

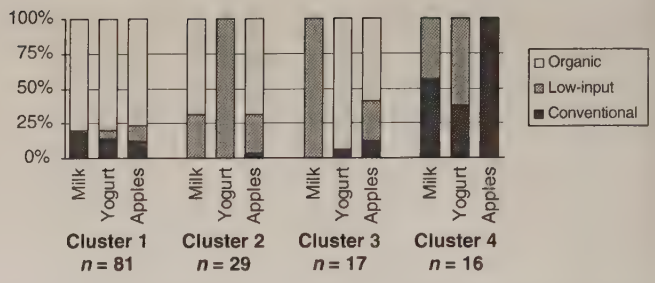

Figure 1. Buying behavior of the four clusters in the purchase simulations.

yogurt, the low-input buyers were split into almost equal groups regarding their second alternative. Altogether, it can be concluded that low-input was perceived as an alternative 'in between' conventional and organic by the great majority of participants.

Buying behavior across the three-product categories

In the purchase simulations, each participant made three consecutive purchase decisions and bought milk, yogurt and apples. Across the whole sample, the order of the three kinds of products (milk, yogurt and apples) rotated evenly. In the descriptive analyses above, results are presented for each of the three product categories separately. We also examined the 'baskets of goods' that people bought, in order to reveal particular buying patterns across the product categories. Initially, participants' buying behavior across the product categories was of interest: 30.9% of participants bought organic products in all three categories, whereas 2.7% each chose exclusively low-input and conventional products (see Table 5). The remaining 63.8% of participants bought 'mixed baskets of goods'. This relatively high share of participants with mixed purchases was also reflected elsewhere in the data: taking into consideration all three purchase decisions per participant, the great majority (85.2%) of participants bought at least one organic product; about half (49.7%) of the participants chose at least one low-input product and around one-third (33.6%) bought at least one conventional product.

Grouping participants with similar buying behavior by cluster analysis

Buying behavior of the clusters (Fig. 1).

- **Cluster 1 'Organic buyers':** Cluster 1 had the highest overall share of organic buyers. In all three-product categories, more than three-quarters of the cluster members chose the organic alternatives. Interestingly, if a product was not bought in organic quality, Cluster 1 members preferred conventional alternatives. These accounted for small shares of less than 20%, whereas low-input products played an almost negligible role. A high-organic affinity was also reflected in the mean organic index, which was the highest of all clusters (6.9 points). Similarly, the stated usual buying behavior for milk, yogurt and apples featured the highest shares of organic purchases of all clusters.
- **Cluster 2 'Additive avoiders':** All members of Cluster 2 bought low-input yogurt without artificial additives. Regarding milk and apples, about 70% of cluster members chose organic and the others low-input products. With one exception, no conventional products were bought. Four people chose all products in low-input quality. For the majority of cluster members, organic quality was important for unprocessed products. Regarding fruit yogurt (a processed product), however, the absence of artificial additives seemed being sufficient to meet their needs. The great majority of Cluster 2 usually bought conventional yogurt, whereas the stated usual buying behavior for milk and apples showed considerable shares of organic buyers. Cluster 2 had the second highest mean organic index of the clusters (6.6 points).
- **Cluster 3 'Concerned about animal welfare':** All members of Cluster 3 bought milk 'from pasture-raised cows'. Also regarding yogurt, the buying behavior was (almost) unanimous: with one exception, all members bought organic yogurt. Only for apples, the choice varied with organic apples being bought most often followed by low-input. A comparison with the stated usual buying behavior revealed two-thirds of people substituted conventional milk with milk 'from pasture-raised cows', whereas the remaining one-third usually bought either organic, or one-half each organic and conventional milk. Regarding yogurt, almost half of the cluster members usually bought conventional products, which were substituted with organic yogurt in the purchase simulations. Similarly, the majority of cluster members usually bought conventional apples. In the purchase simulations, these were mostly substituted with low-input or organic apples. Cluster 3 had the third highest mean organic index (5.9 points).
- **Cluster 4 'Conventional buyers':** Cluster 4 members exclusively bought conventional and low-input products in the purchase simulations. Accordingly, their stated usual buying behavior featured the highest shares of conventional buyers of all clusters. Cluster 4 had the

Table 6. Attitudes regarding food quality and safety.

Statements[1]	Cluster (C) means				Clusters compared: tests of equality of cluster means		
	C 1	C 2	C 3	C 4	*F*-value[2]	Welch-value[3]	*P*-value
a. Pesticide residues in fruit and vegetable are harmful to human health.	4.74	4.69	4.53	4.63		0.463	0.710
b. Genetically modified food is a danger to human health.	4.51	4.07	4.00	3.50		5.017**	0.005
c. I usually buy apples from Germany.	4.05	4.00	3.82	4.50	1.283		0.283
d. I am willing to pay considerably higher prices for food that has considerable higher quality standards.	3.72	3.48	3.65	3.31	1.465		0.227
e. Artificial flavors and additives in food are harmful to human health.	3.86	3.45	3.71	2.88	4.325**		0.006
f. I trust food more that was produced in Germany.	3.41	3.69	3.59	4.31		5.549**	0.003
g. I only buy yogurt that I know was produced without artificial additives.	3.26	3.10	3.53	3.19	0.379		0.768
h. I think that organic products are too expensive.	2.86	3.14	2.94	4.50	11.858***		0.000
i. I generally buy organic food.	3.15	2.69	2.82	2.06	8.504***		0.000
j. I generally do not buy products including preserving agents.	2.90	2.79	2.41	3.00	0.818		0.486
k. When buying milk, I do not think about how the cows were kept.	2.49	2.48	1.88	3.88		8.607***	0.000
l. The taste of meals is more important than the ingredients.	2.21	2.48	2.41	2.63	0.931		0.428
m. When I try new products, I do not usually check the list of ingredients.	2.19	2.28	2.12	2.81	1.078		0.360
n. Milk from cows kept on pastures during summer is as healthy as milk from cows kept in stables all year round.	1.93	1.79	2.18	2.19	0.795		0.499
o. I often prepare ready-to-eat meals instead of cooking myself.	1.77	1.93	2.06	2.31	1.596		0.193
p. I am bored of discussions about nutrition and health.	1.57	1.79	1.94	2.25	2.682*		0.049

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

[1] Likert-scaled questions with 5 = strongly agree, 4 = slightly agree, 3 = neither agree nor disagree, 2 = slightly disagree, 1 = strongly disagree.

Two of the original 18 statements were excluded from the analysis due to contradictions in understanding across the sample. These statements are not listed here.

[2] The *F*-test was used for those statements for which equality of variances in the clusters can be assumed (based on Levene's test for equality of variances).

[3] The Welch-test was used for those statements for which equality of variances in the clusters cannot be assumed (based on Levene's test for equality of variances).

second highest shares of low-input buyers for milk and yogurt of all clusters, whereas all members bought conventional apples. Cluster 4 had the lowest mean organic index (5.4 points).

Attitudes toward food quality and safety. The comparison of the four clusters regarding attitudes toward food quality and safety by means of an ANOVA revealed seven statements with high discriminatory power (see Table 6). Altogether, the most significant differences existed between 'Organic buyers' (Cluster 1) and 'Conventional buyers' (Cluster 4). According to our results, the 'Organic buyers' (Cluster 1) were consumers with a great interest in health, nutrition and organic food. They perceived GM food and artificial flavors and additives as harmful to human health. Of all clusters, they expressed the least trust in food from Germany. By contrast, the 'Conventional buyers' (Cluster 4) were rather carefree consumers. In accordance with their buying behavior, they found organic products too expensive. Cluster 4 members expressed lower concerns regarding GM food and artificial flavors and additives, and they generally trusted food produced in Germany. Clusters 2 and 3 represented less distinct groups that did not differ significantly from each other for any of the statements. Compared with Clusters 1 and 4, only a few significant differences could be detected. Most importantly, Clusters 2 and 3 expressed a more positive attitude toward organic food and cared more about animal husbandry than Cluster 4. Interestingly, no significant differences between the socio-demographic compositions of the clusters could be detected.

Discussion and Conclusions

The cluster analysis showed interesting insights regarding low-input products. Most strikingly, low-input products attracted two different groups of buyers: first, people who usually buy mostly conventional products (Cluster 4), and

secondly, people who usually buy conventional products in particular categories and organic in others (Clusters 2 and 3). More regular organic buyers (Cluster 1), in contrast, did not favor low-input products. Moreover, low-input products mainly substituted conventional products. Overall, the low-input alternatives of the three-product categories did not necessarily attract the same group of people. One striking result of our study was that we did not identify a consumer segment of 'typical low-input-buyers'. This is not surprising, given that three very different attributes were tested, referring to aspects of animal husbandry for milk, food additives for yogurt, and the use of pesticides for apples. It is therefore hard to predict the potential success of individual low-input products in the market-place. Nevertheless, some general implications can be derived from our studies that are discussed in the following sections.

Characteristics of organic consumers

Similar to previous studies[8,29], our data indicate that demographic characteristics alone do not sufficiently explain the propensity to buy organic. Our results furthermore confirm the findings by Hughner et al.[8] in which occasional organic consumers are considered a heterogeneous group. First, we found different patterns in buying behavior across the sample. For example, some people bought organic yogurt but non-organic milk and others vice versa. Second, our findings are consistent with previous research showing that motivations and attitudes provide reasons for differences in buying behavior[8,18–21]. Most of the studies mentioned here differentiated between non, occasional and committed consumers. Our study focused on occasional consumers exclusively. While some statements turned out to have little discriminatory power, we still found a number of statements regarding attitudes toward quality and safety that varied between the clusters. We therefore suggest that more research on consumers' motivations, perceptions and understanding of organic production should be conducted, not only comparing committed with occasional consumers but also revealing differences among occasional consumers.

Strategic implications for organic product sales

A previous longitudinal study on household panel data revealed that organic budget shares of households fluctuate in the course of time, especially among not fully committed buyers[27]. Apparently, consumers change their minds regarding organic products, and they are not necessarily loyal over time. The study suggests that consumers frequently switch between organic and conventional products. It is therefore not surprising that a considerable share of consumers switched to alternatives that they usually did not buy. Against the background of fluctuating organic budget shares, we suggest that low-input products can compete with organic products. Especially consumers with a lower propensity to buy organic purchase their organic products mainly at regular supermarkets and discount stores[4,27], which are the same sales channels through which low-input products are distributed. In this consumer segment, low-input might therefore take away future market shares from both conventional and organic products. In comparison with low-input products, organic products incorporate not only one but also many special attributes. The low-input products in our experiments were not certified by an external body and yet they reached shares of 15–30% of the purchases. A concerted communication strategy focusing on tangible aspects of organic production as well as organic certification might be a successful strategy for the organic sector to gain new customers and to differentiate organic products from low-input products.

Limitations of the study

In our study, purchase simulations were conducted to analyze consumers' buying behavior. As with stated preference data in general, the results of the purchase simulations have to be interpreted with care[30]. Foremost, the buying frequencies of the three-product alternatives should not be used to predict market shares for the following reasons. By definition, only occasional consumers participated in the study, and the sample size was relatively small due to budget constraints and the complex design of the study. Furthermore, the offered products were not branded. It thus remains unclear how consumers would have reacted if conventional, low-input and organic products with well-known brands had been used in the purchase simulations. Nevertheless, stated preference data generally provide a good picture about overall trends[31]. While the success of the tested products in reality remains unknown, it is possible to derive general implications and reveal needs for future research from stated choice data.

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Use of an integrative soil health test for evaluation of soil management impacts

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Abstract

Understanding the response of soil quality indicators to changes in management practices is essential for sustainable land management. Soil quality indicators were measured for 2 years under established experiments with varying management histories and durations at four locations in New York State. The Willsboro (clay loam) and Aurora (silt loam) experiments were established in 1992, comparing no-till (NT) to plow-till (PT) management under corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation. The Chazy (silt loam) trial was established in 1973 as a factorial experiment comparing NT versus PT and the crop harvesting method (corn silage versus corn grain). The Geneva (silt loam) experiment was established in 2003 with vegetable rotations with and without intervening soil building crops, each under three tillage methods (NT, PT and zone-till (ZT)) and three cover cropping systems (none, rye and vetch). Physical indicators measured were wet aggregate stability (WAS), available water capacity (AWC) and surface hardness (SH) and subsurface hardness (SSH). Soil biological indicators included organic matter (OM), active carbon (AC), potentially mineralizable nitrogen (PMN) and root disease potential (RDP). Chemical indicators included pH, P, K, Mg, Fe, Mn and Zn. Results from the Willsboro and Aurora sites showed significant tillage effects for several indicators including WAS, AWC, OM, AC, pH, P, K, Mg, Fe and Mn. Generally, the NT treatment had better indicator values than the PT treatments. At the Chazy site, WAS, AWC, OM, AC, pH, K and Mg showed significant differences for tillage and/or harvest method, also with NT showing better indicator values compared to PT and corn grain better than corn silage. Aggregate stability was on average 2.5 times higher in NT compared to PT treatments at Willsboro, Aurora and Chazy sites. OM was also 1.2, 1.1 and 1.5 times higher in NT compared to PT treatments at Willsboro, Aurora and Chazy sites, respectively. At the Geneva site WAS, SH, AC, PMN, pH, P, K and Zn showed significant tillage effects. The cover crop effect was only significant for SH and PMN measurements. Indicators that gave consistent performance across locations included WAS, OM and AC, while PMN and RDP were site and management dependent. The composite soil health index (CSHI) significantly differentiated between contrasting management practices. The CSHI for the Willsboro site was 71% for NT and 59% for PT, while at the Aurora site it was 61% for NT and 48% for PT after 15 years of tillage treatments.

Key words: soil quality, soil health, tillage, soil quality indicators, Cornell Soil Health Test

Introduction

Soil quality relates to the capacity of the soil to function in supporting important ecosystem services without a negative interaction with the environment[1]. This concept of soil quality integrates soil chemical, physical and biological attributes, and has recently attracted attention due to an increased awareness of the impact of soil management on agricultural production and environmental quality[2]. The interactions of soil chemical, physical and biological properties often determine how effectively the soil performs ecosystem functions such as nutrient retention and release, partitioning of rainfall into runoff and infiltration, moisture retention and release, resistance to environmental degradation and buffering environmental pollutants[1,3]. The desire to maintain and improve agricultural productivity without jeopardizing environmental sustainability has increased the demand for assessment tools to measure

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directional changes in soil quality in relation to these various processes.

Since overall soil quality cannot be measured directly, its assessment relies on selected soil measurements (indicators) to quantify the management-induced changes in a soil system[1,2,4]. The group of soil quality indicators that best describes changes in response to management practices constitutes the minimum data set (MDS) for a particular management goal[5,6]. A good MDS for soil quality assessment should encompass ecosystem processes, integrate soil physical, chemical and biological properties and processes, be accessible to many users and applicable to field conditions, be sensitive to variations in management and climate, and where possible, be components of existing soil databases[1,2,7]. Land managers need easily measurable soil attributes or indicators to assess soil functions in relation to management practices. This task involves the selection of appropriate indicators that will fit the intended management goals.

Most soil quality assessment tools combine a given set of soil measurements (MDS) that cut across the soil physical, chemical and biological measurements, and interpret the measured values through scoring curves and indexing[8–10]. Challenges that face these soil quality assessment tools include (i) the selection of the appropriate indicators for different scenarios and management goals; (ii) the interpretation of the indicators in relation to the inherent soil characteristics; (iii) relating soil quality indexes to management goals and (iv) coping with site-specific issues[11]. For adequate transferability of these assessment tools, the above issues need to be carefully considered and addressed.

The recently developed Cornell Soil Health Test (CSHT) is an integrative farmer-oriented soil quality assessment tool consisting of 15 soil indicators that include physical chemical and biological soil properties[10,12]. The CSHT can assist growers to identify soil constraints that are limiting crop production and target specific management practices to address identified problem areas[10].

As shown by several soil quality studies, the selection of suitable indicator(s) cannot be universally achieved due to the diversity of management goals, soil types, climatic regions, agro-ecosystem management practices and interseasonal variations[6,12–14]. In order to achieve standards for soil quality assessment, data are needed from different regions that quantify the performance of soil quality indicators in the short- and long-term across different sites, management systems and soils[14]. Using existing short- and long-term research trials can help achieve the goal of understanding how management practices affect soil functions in different soils and at different locations[15–17].

Karlen et al.[6] studied soil quality at three northern corn/soybean belt locations using long-term plots in different rotation systems. Most of the indicators assessed showed significant treatment differences at different locations, but in general, total organic matter (OM) was the most sensitive indicator across these locations, while bulk density (BD) was significant only at one location.

Liebig et al.[18] assessed soil quality for two long-term cropping system trials in North Dakota and found that management effects on soil quality were largely limited to the surface 0.075 m and increased over time. Continuous crop–no-till had more favorable organic carbon, particulate OM, potentially mineralizable nitrogen (PMN), microbial biomass, aggregate stability and infiltration rates compared to the crop–fallow conventional tillage system.

While studies on the effects of long-term management systems on soil quality indicators have been reported in many regions of the United States[5,6,14–18], comparatively fewer studies have focused on the cooler northeastern part of the USA. Understanding how management practices affect soils in the northeast will help in developing useful indicators for assessing the current status and detecting changes resulting from management[14]. This study seeks to fill the information gap on the performance of soil quality indicators in long-term cropping trials. Our study is therefore focused on identifying changes in soil quality indicators on selected long-term experimental sites located across New York State. Our objectives were to examine how soil physical, biological and chemical indicators as assessed in the CSHT are affected by different management systems, soil types and time, and to evaluate the composite soil quality index in distinguishing between contrasting soil management practices at these sites.

Materials and Methods

Site description

Four established tillage and rotation trials located on research facilities of Cornell University (Chazy, Willsboro, Aurora and Geneva, NY) were used in this investigation.

Long-term tillage/silage experiment in Chazy, NY. The Chazy experimental site (44°53′N, 73°28′W) was established in 1973 and planted to continuous maize (*Zea mays* L.). The soil type at this site is Raynham silt loam, coarse-silty, mixed, active and non-acidic mesic Aeric Epiaquept[19]. The design of this trial is a factorial (2×2) randomized complete block with treatment combinations replicated four times, including two tillage treatments [no-till (NT) versus plow-till (PT)] and two harvest method treatments [corn silage with stover harvested and removed from the plots (COS) versus corn grain with stover returned to plots as residue (COG)], giving a total of four treatment combinations. The PT plots were moldboard plowed and disked each year and planted to maize, while the NT plots were left untilled and planted using a NT planter. For the COS treatments, the above-ground biomass was harvested yearly and removed from the plots, while in the COG treatments only the ears were harvested each year and the rest of the crop biomass was left as residue.

Tillage experiment in Willsboro and Aurora, NY. Identical tillage trials were located in Willsboro (44°22′N, 73°26′W) and Aurora, NY (42°44′N, 76°39′W), both

established in 1992, using spatially balanced complete block designs[20] with four replications. The Aurora experiment is located on a Honeoye-Lima silt loam (fine-loamy, mixed, active, mesic Glossic Hapludalf and Oxyaquic Hapludalf) and the Willsboro tillage trial on a Kingsbury silty clay (fine, illitic and frigid Aeric Ochraqualf)[19]. The tillage treatments were moldboard PT and NT under a corn–soybean (*Glycine max* L.) rotation.

Gates experimental farm in Geneva, NY. The Gates Farm in Geneva, NY (42°52′N, 77°03′W) is a 6-ha site that consists of a total of 72 plots with three tillage [NT, zone-till (ZT), and PT], three cover crop (no cover, rye and vetch) and two rotation treatments. The soil type is a mixture of Kendaia silt loam (mixed, active, nonacid and mesic Aeric Endoaquept) and Lima silt loam (mixed, active and mesic Oxyaquic Hapludalf[19]), although Kendaia silt loam is predominant. The experiment was established in 2003. The first rotation (R1) involved continuous high-value vegetable production, while the second rotation (R2) incorporates season-long soil-building crops.

Cover crops [rye (*Secale cereale*) or vetch (*Vicia villosa* L.)] were established in early fall and killed with glyphosate in the spring. ZT was established each spring using a zone builder equipped with a deep ripping shank. Usually, the width of the planting zones was 0.015 m and depth of ripping was about 0.3 m. PT consisted of moldboard plowing and disking to create the seedbed. The cropping sequence (2003–2007) for the continuous vegetable rotation (R1) was bean (*Phaseolus vulgaris* L.)–beet (*Beta vulgaris* L.)–sweet corn–cabbage (*Brassica oleracea* var. *capitata* L.)–bean; while the same sequence for the soil building rotation (R2) was bean–field corn–clover/barley (*Trifolium* spp. L./*Hordeum vulgare* L.)–sweet corn–bean.

Sampling and laboratory methods

Soil samples from the experimental sites were collected at two time periods, which were 2004 and 2007 at the Chazy, Aurora and Willsboro sites, and 2006 and 2007 at the Geneva site. Soil sampling, processing and analysis for all trials in 2006 and 2007 were performed according to the CSHT protocol[10,21]. Soil sampling occurred in the early spring (April) of each year at a depth of 0–0.15 m except for 2004, which was at a depth of 0.025–0.175 m. Physical indicators measured included wet aggregate stability (WAS), available water capacity (AWC), surface hardness (SH) and subsurface hardness (SSH). The biological indicators measured were total OM, active carbon (AC), PMN and root disease potential (RDP). The chemical indicators assessed were pH, extractable P, extractable K, Mg, Fe, Mn and Zn. All measurements were performed on disturbed soil samples except for SH and SSH, which were assessed in the field at approximate field capacity water contents using a soil penetrometer. For 2004 samples from Aurora, Chazy and Willsboro, AWC was determined from intact soil cores taken from the field and field penetration resistance was not determined.

Table 1. Soil textural analysis of the study sites.

Site	Sand ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Clay ($g\,kg^{-1}$)	Textural class
Chazy tillage trial	212	726	62	Silt loam
Willsboro tillage trial	195	491	314	Clay loam
Aurora tillage trial	408	484	108	Silt loam
Gates Farm tillage/ rotation trial	470	445	85	Silt loam

WAS was measured by a rainfall simulation method[22], applying 2.5 J of energy for 300 s on aggregates (2–0.25 mm) placed on a 0.25 mm mesh sieve[21]. The fraction of soil aggregates remaining on the sieve, after correcting for the stones and other particles >0.25 mm, was regarded as the percent WAS. AWC was determined from disturbed soil samples that were air-dried and passed through a 2 mm mesh sieve. Soil moisture apparatus was used to equilibrate the soil to pressures of −10 and −1500 kPa. The gravimetric moisture content difference between these two pressures after the soil samples had attained equilibrium was regarded as the AWC.

Soil hardness was assessed using a soil compaction tester (Dickey-John[23], Auburn, IL) at depths of 0–0.15 and 0.15–0.45 m to quantify SH and SSH, respectively. The maximum penetration resistances were recorded at these depths as SH and SSH values.

OM was determined by the loss on ignition method[24]. AC was measured by the permanganate oxidation method described by Weil et al.[25]. PMN was determined using the seven-day anaerobic incubation technique as described by Drinkwater et al.[26]. RDP was assessed using the bean-bioassay method developed by Abawi et al.[27].

The chemical elements were analyzed with an ICP mass spectrophotometer after extraction with Morgan's solution (0.72 N NaOAc + 0.52 N CH_3COOH) buffered at pH 4.8 according to the routine procedures of the Cornell Nutrient Analytical Laboratory.

Additionally, the textural analysis of the soils at different sites was assessed using a rapid quantitative method developed by Kettler et al.[28]. The mean sand silt and clay contents for each experimental site are presented in Table 1.

The composite soil health index (CSHI) was calculated from the individual indicator scores, which were obtained from the scoring functions[10]. The CSHI is a linear unweighted combination of the indicator scores normalized to a scale of 100[21].

Statistical methods

Analysis of variance (ANOVA) was performed on the measured data from the different experimental sites based on the experimental designs of the respective trials. Separate analyses were performed for 2004 and 2007 data since the sampling depths differed for both years. For the Gates Farm trial in Geneva, we analyzed results from 2006 and 2007 together since the sampling protocol was identical for

Table 2. Significance levels and mean values of the measured soil quality indicators at Willsboro and Aurora site during 2004 and 2007.

Soil quality indicators	*P* level for tillage 2004	Mean 2004		*P* level for tillage 2007	Mean 2007	
		PT	NT		PT	NT
Willboro tillage trial (15 years on Kingsbury clay loam soil)						
Aggregate stability (%)	0.0001	30.4	68.9	0.0064	22.4	60.2
AWC ($g\,g^{-1}$)	ns	0.145	0.163	ns	0.153	0.131
SH (MPa)	ND	–	–	ns	0.29	0.42
SSH (MPa)	ND	–	–	ns	1.21	1.12
OM ($g\,kg^{-1}$)	0.0404	46	57	ns	39	48
AC ($mg\,kg^{-1}$)	0.0645	582	710	ns	614	637
PMN ($\mu g\ N\,gdw\ soil^{-1}\,week^{-1}$)	0.0247	5.5	10.6	ns	4.3	9.6
Root health (1–9)	ns	2.3	1.6	ns	3.2	2.3
pH	0.0738	6.3	5.7	0.374	6.1	5.9
Phosphorus ($mg\,kg^{-1}$)	0.0015	2.6	5.3	ns	2.6	3.0
Potassium ($mg\,kg^{-1}$)	ns	115	99	ns	78.9	72.5
Magnesium ($mg\,kg^{-1}$)	ns	568	470	ns	560	495
Iron ($mg\,kg^{-1}$)	ns	16.8	17.8	ns	13.3	10.6
Manganese ($mg\,kg^{-1}$)	ns	18.3	12.3	0.0048	17a	9b
Zinc ($mg\,kg^{-1}$)	ns	0.957	0.739	ns	0.625	0.637
CSHI (%)	ND	–	–	0.0844	58.9	71.1
Aurora tillage trial (15 years Lima silt loam soil)						
Aggregate stability (%)	0.0193	19.2	48.7	0.0008	17.2	41.2
AWC ($g\,g^{-1}$)	0.0003	0.110	0.168	ns	0.115	0.123
SH (MPa)	ND	–	–	ns	0.66	0.74
SSH (MPa)	ND	–	–	ns	2.03	2.01
OM ($g\,kg^{-1}$)	0.0734	24	27	0.0025	27	31
AC ($mg\,kg^{-1}$)	ns	564	551	0.0010	435	560
PMN ($\mu g\ N\,gdw\ soil^{-1}\,week^{-1}$)	ns	7.7	5.7	ns	6.0	7.2
Root health (1–9)	ns	3.7	2.8	ns	2.8	3.0
pH	ns	7.7	7.8	0.0117	8.0	8.1
Phosphorus ($mg\,kg^{-1}$)	ns	5.7	9.1	0.0199	6.3	12.1
Potassium ($mg\,kg^{-1}$)	ns	38	37	0.0334	41	53
Magnesium ($mg\,kg^{-1}$)	ns	337	345	0.0258	311	346
Iron ($mg\,kg^{-1}$)	0.0105	1.21	0.59	ns	0.67	0.50
Manganese ($mg\,kg^{-1}$)	ns	15.1	13.2	ns	16.2	15.3
Zinc ($mg\,kg^{-1}$)	ns	0.314	0.281	ns	0.475	0.500
CSHI (%)	ND	–	–	0.0046	48.3	60.6

ND, not determined; ns, not significant.

both years. Because of the complexity of the experimental design at Gates Farm, especially when both years of measurement are analyzed together, we treated each rotation separately. Mean separation was computed using the Turkey test after a significant *F*-ratio ($P < 0.05$) in ANOVA was observed.

Principal component analysis (PCA) was used to study the groupings of different treatment factors for the Chazy, Aurora and Willsboro trials. The factor components were plotted in two-dimensional spaces to explore possible groupings within the dataset. All analyses were performed using the SPSS statistical software[29].

Results and Discussion

Soil physical indicators

WAS was significantly different for tillage treatments at all sites that were sampled (Tables 2–4). The tillage contrast at Willsboro, Aurora and Chazy sites showed that the WAS values were more than double in NT treatments compared to PT in both years of measurement (Tables 2 and 3). The differences of the WAS under the tillage treatments in R1 and R2 at Gates Farm were less pronounced, presumably due to the shorter time period of the treatment effects (Table 4). The ZT treatment had higher WAS than the NT and the PT treatments for R1, while the NT had the highest WAS for the R2. The robustness of WAS as a soil quality indicator has been highlighted in many studies[12,30,31]. Aggregate stability is a soil physical indicator that is related to biological and chemical processes in the soil[32,33]. The significance of WAS for tillage for all sites suggests that tillage management can affect aggregation and structural stability of the surface soil both in the short and long term. Although Gates Farm trial was only 3 years old, significantly higher WAS in the minimum tillage practices could be detected (Table 4). For the longer-term trials, the

Table 3. Significance levels and mean values of the measured soil quality indicators at Chazy site during 2004 and 2007.

Soil quality indicators	*P* level for tillage	Mean		*P* level for harvest treatment	Mean	
		PT	NT		Silage	Corn grain
2004						
Aggregate stability (%)	0.0001	17.6	45.6	0.0749	27.6	35.6
AWC ($g\,g^{-1}$)	0.0001	0.202	0.249	0.0031	0.212	0.239
SH (MPa)	ND	–	–	ND	–	–
SSH (MPa)	ND	–	–	ND	–	–
OM ($g\,kg^{-1}$)	0.00001	25	34	0.0291	28	31
AC ($mg\,kg^{-1}$)	0.0002	461	682	0.0067	506	637
PMN ($\mu g\ N\,gdw\ soil^{-1}\,week^{-1}$)	0.0450	1.01	1.69	ns	1.10	1.60
Root health (1–9)	ns	1.8	1.5	0.0495	1.9	1.4
pH	0.0002	8.1	7.8	ns	7.9	7.9
Phosphorus ($mg\,kg^{-1}$)	ns	9.8	8.9	ns	8.6	10.1
Potassium ($mg\,kg^{-1}$)	ns	34.5	37.1	0.0015	25.7	45.8
Magnesium ($mg\,kg^{-1}$)	0.0177	150	177	0.0034	145	181
Iron ($mg\,kg^{-1}$)	ns	1.47	1.09	ns	1.16	1.40
Manganese ($mg\,kg^{-1}$)	0.0361	15.0	12.3	ns	13.2	14.1
Zinc ($mg\,kg^{-1}$)	0.042	0.32	0.48	ns	0.39	0.41
CSHI (%)	ND	–	–	ND	–	–
2007						
Aggregate stability (%)	0.00001	22.6	55.6	0.0373	34.8	43.3
AWC ($g\,g^{-1}$)	0.0152	0.194	0.178	ns	0.185	0.187
SH (MPa)	0.0543	0.57	1.03	ns	0.94	0.66
SSH (MPa)	ns	2.43	2.32	ns	2.34	2.41
OM ($g\,kg^{-1}$)	0.00001	21	33	ns	27	27
AC ($mg\,kg^{-1}$)	0.00001	449	658	0.0385	522	584
PMN ($\mu g\ N\,gdw\ soil^{-1}\,week^{-1}$)	ns	3.19	3.36	ns	2.88	3.67
Root health (1–9)	ns	2.2	2.3	ns	2.3	2.2
pH	0.0018	8.1	8.0	ns	8.1	8.1
Phosphorus ($mg\,kg^{-1}$)	0.0483	8.6	11.9	ns	10.4	10.0
Potassium ($mg\,kg^{-1}$)	ns	28.4	31.6	0.00001	22.2	37.8
Magnesium ($mg\,kg^{-1}$)	ns	135	167	0.417	133	169
Iron ($mg\,kg^{-1}$)	ns	1.50	0.94	ns	1.13	1.31
Manganese ($mg\,kg^{-1}$)	ns	14.1	10.8	ns	11.5	13.4
Zinc ($mg\,kg^{-1}$)	ns	0.29	0.50	ns	0.44	0.35
CSHI (%)	0.00001	43.9	55.8	0.0033	47.1	52.6

ND, not determined; ns, not significant.

differences due to tillage treatments were more pronounced. Other previous studies have also shown that the soil aggregate stability is improved by reducing tillage[18,34].

WAS was significant for the harvest method treatments during both years at the Chazy site (Table 3). The corn grain treatment (COG), which had the crop stover returned as residue, had 24–29% higher WAS than the silage treatment (COS), which had all the corn stover removed. This highlights the favorable effect of plant residues for the formation of water stable aggregates[35]. However, the effect of stover returned on WAS was not as strong as the effect of tillage, as the relative percentage increase in WAS due to NT was 159% in 2004 and 146% in 2007 (Table 3). Singh and Malhi[36], working in the cool temperate region of western Canada, also showed that the soil aggregation benefited more from NT than from residue retention. This highlights the importance of tillage in the overall management of soil quality. Reducing tillage has a long-term beneficial effect on soil aggregation thereby making the soil surface more resistant to soil erosion and promoting better infiltration of water into the soil.

The cover crop effect on WAS was not significant for both rotations at the Geneva site (Table 4), presumably as a result of the shorter time period of treatment application. This relatively short duration of cover crops to the period of sampling (3 and 4 years, respectively) might not be sufficient for the treatment effects to become apparent. The Gates Farm soil had previously been in continuous vegetable rotation for many years as part of a commercial operation. Some of the lowest values for WAS in this study were measured on Gates Farm plots. Due to this intense level of degradation, it may take a longer time before the effect of the cover crops begins to reflect on soil aggregation.

Table 4. Significance levels and mean values of the measured soil quality indicators at the Gates Farm, Geneva site for two-rotation measured in 2006 and 2007 (results combined).

Soil quality indicators	*P* level for tillage	Mean			*P* level for cover crops	Mean		
		PT	ZT	NT		No-cover	Rye cover	Vetch cover
Rotation 1[1]								
Aggregate stability (%)	0.0027	14.4b	19.8a	16.0b	ns	16.5	16.0	17.7
AWC ($g\,g^{-1}$)	ns	0.118	0.121	0.117	ns	0.117	0.118	0.120
SH (Mpa)	0.0070	0.85b	1.10a	0.99ab	0.0044	0.90b	0.94b	1.10a
SSH (Mpa)	ns	1.90	2.07	2.01	ns	1.98	2.00	2.01
OM ($g\,kg^{-1}$)	ns	22	21	19	ns	21	20	20
AC ($mg\,kg^{-1}$)	0.0177	516a	550a	437b	ns	501	510	492
PMN (μg N gdw $soil^{-1}\,week^{-1}$)	0.0415	3.47b	6.23a	3.74b	0.0002	3.41b	3.76b	6.27a
Root health (1–9)	ns	5.3	4.9	4.9	ns	5.0	5.0	5.1
pH	0.0041	7.36a	7.28a	7.02b	ns	7.24	7.22	7.19
Phosphorus ($mg\,kg^{-1}$)	0.0003	9.7b	14.5a	8.4b	ns	10.9	11.5	10.2
Potassium ($mg\,kg^{-1}$)	0.0063	46b	75a	54b	ns	58	57	60
Magnesium ($mg\,kg^{-1}$)	ns	175	165	154	ns	166	166	162
Iron ($mg\,kg^{-1}$)	ns	4.03	2.67	3.02	ns	4.39	2.59	2.73
Manganese ($mg\,kg^{-1}$)	ns	20.0	20.2	21.1	ns	21.0	20.7	19.6
Zinc ($mg\,kg^{-1}$)	0.0016	0.52b	0.77a	0.59b	ns	0.65	0.61	0.63
CSHI (%)	0.0863	49.5b	53.5a	51.2ab	ns	51.7	51.3	51.2
Rotation 2[2]								
Aggregate stability (%)	0.0261	19.5b	19.8b	26.4a	ns	21.8	22.4	21.4
AWC ($g\,g^{-1}$)	ns	0.118	0.126	0.121	ns	0.121	0.124	0.120
SH (Mpa)	0.0004	1.19b	1.20b	2.01a	ns	1.11	1.19	1.16
SSH (MPa)	ns	2.13	1.93	2.10	ns	2.01	2.13	2.01
OM ($g\,kg^{-1}$)	ns	24	20	22	ns	23	21	21
AC ($mg\,kg^{-1}$)	ns	539	509	553	ns	549	525	527
PMN (μg N gdw $soil^{-1}\,week^{-1}$)	ns	6.71	5.85	6.70	ns	6.94	5.91	6.42
Root health (1–9)	ns	5.1	4.9	4.7	ns	5.0	4.7	5.0
pH	0.0217	7.18b	7.45a	7.09b	ns	7.19	7.24	7.29
Phosphorus ($mg\,kg^{-1}$)	ns	10.0	12.6	10.9	ns	11.0	10.9	11.6
Potassium ($mg\,kg^{-1}$)	ns	56	67	67	ns	62	65	63
Magnesium ($mg\,kg^{-1}$)	ns	175	164	157	ns	171	162	162
Iron ($mg\,kg^{-1}$)	ns	1.94	2.40	2.91	ns	1.72	3.50	2.03
Manganese ($mg\,kg^{-1}$)	ns	21.9	20.4	22.5	ns	21.6	21.3	21.9
Zinc ($mg\,kg^{-1}$)	ns	0.62	0.70	0.71	ns	0.68	0.70	0.65
CSHI (%)	ns	52.5	55.8	55.5	ns	55.6	54.5	53.7

ND, not determined; ns, not significant; a, b, c, significant homogeneous groups.
[1] Rotation 1: (2003–2007) bean–beet–sweet corn–cabbage–bean.
[2] Rotation 2: (2003–2007) bean–field corn–clover/grain–sweet corn–bean.

The clay loam site in Willsboro had higher ranges of WAS than the silt loams at Chazy, Aurora and Geneva sites (Tables 2–4). The general range of WAS for the PT treatment at the silt loam sites was between 14 and 23%, while it was about 30% at the clay loam site. This highlights the importance of soil genetic characteristics in soil quality assessment. The significant role of clay and clay/OM complexes in the formation of stable soil aggregates has been shown in previous studies[37–39]. Therefore, consideration should be given to soil type factors in developing soil quality assessment frameworks.

Significant differences in AWC due to tillage treatment were observed only for the Aurora and Chazy experiments for 2004 (Tables 2–4). For the sites (Willsboro and Geneva) where AWC was not significant with tillage, there was a general shift of higher AWC towards reduced tillage (NT and ZT). The 2007 AWC results at the Chazy and Willsboro sites showed that the PT treatment had higher AWC than the NT treatment (Tables 2 and 3). This may be related to the method of measurement. In 2004, AWC was determined using the undisturbed soil core method, while in 2007, a simplified method was used in which measurements were performed on the disturbed soil samples. By disturbing the soil samples, the impact of soil structure on AWC becomes masked especially at the lower suctions, and the different pore sizes that would have contributed to

AWC, especially in the NT system, have been disrupted and only the effect of soil matrix on moisture retention was being captured from the disturbed samples. This highlights the problems and trade-offs encountered in developing simple soil quality assessment methods. Disturbed soil samples are much easier to collect and handled than the soil cores[10], but *in situ* core samples can yield better information in relation to some important soil characteristics.

AWC was significantly different between the COS and COG treatments at Chazy in 2004 but not in 2007. The COG treatment had 13% higher AWC than the COS treatment in 2004 compared to almost no difference detected between them in 2007 (Table 3). The lack of significant difference in 2007 may be linked to using disturbed soil samples for AWC determination as discussed above. A relatively higher level of OM in the COG and in NT systems was expected to produce a better-structured soil with higher moisture retention.

The SH and SSH were not significant with tillage treatments for the Willsboro and Aurora trials (Table 2). The values of SSH at field capacity measured for the Willsboro clay loam (1.21 MPa for PT and 1.12 MPa for NT) were relatively low (Table 2) and less than the 2 MPa defined as the threshold beyond which the root growth becomes severely impaired[40,41]. In the Aurora trial, the field capacity SSH values were slightly above the 2 MPa limit, indicating some measure of subsurface soil hardness in contrast to the Willsboro site (Table 2). The SSH values measured at the Chazy site were higher than those measured from the other sites with SSH values for the PT and NT treatments being 2.42 and 2.33 MPa, respectively (Table 3). This indicates that SSH may be a constraint in the Chazy soil especially under the PT treatment (suggesting a plow pan). Although there were no significant differences in SH at most of the sites, the quantitative values of SH for NT treatments were always higher than for the PT treatments (Tables 2–4). The tendency for the NT system to have higher penetration resistances has been highlighted by several authors[42–45], although this may not necessarily constitute a hindrance to root growth and development due to improved soil structure and preserved bio-channels[42].

Although BD measurement was not assessed in the trials presented in this paper, it is generally difficult to predict how it may have been impacted by different treatments. Pikul et al.[17] found that at five locations in the Great Plains where NT was compared to PT in long-term trials, tillage resulted in increased, unchanged or decreased BD, showing a lack of consistent trend. Karlen et al.[6], also found that BD was significantly affected by crop rotations in only one out of the four long-term trials that were evaluated in Iowa and Wisconsin. It is therefore important to measure BD directly in order to evaluate how it has been affected by different treatments in long-term trials.

While BD may not show a consistent trend in the direction of better management practices, it may, however, prove useful in normalizing some other measured indicators to a volume basis, thereby reducing errors of result interpretations.

Soil biological indicators

OM content consistently showed significant differences with management in long-term experimental plots at the Willsboro, Aurora and Chazy sites, always in the direction of the conservation management practices, i.e. NT>PT and COG>COS (Tables 2 and 3). The increase in OM of the surface soil (< 0.3 m) under NT compared to PT systems has been reported in several studies[46,47]. Intensive soil tillage that occurs under PT treatments produces disturbances and soil structural modifications, thus increasing the potential for OM losses from the surface soil by exposing more residue material to biological oxidation[48]. However, recent evaluation on the effects of tillage on OM losses indicates a more complex picture, which suggests that NT mostly results in a redistribution of OM, with more near the surface and less accumulation in the subsoil[46]. From this study, we cannot conclude that NT resulted in higher OM levels for the entire soil profile since our samples were obtained from the surface layer (0–0.15 m).

Although the direction of significant differences was the same, the magnitude of the differences between the NT and the PT treatment reflected the effects of soil type and the length of the trial. Comparing the Willsboro (clay loam) and Aurora (silt loam) sites with identical length of trial but different soil types showed that both the levels of OM and the average increase due to no tillage was higher for Willsboro than Aurora (24 and 14% higher, respectively). Higher OM accumulation in fine-textured soils may be due to the protection of the adsorbed OM on the clay particles from microbial decomposition[49] and the physical inaccessibility of the OM within pores of micro-aggregates by soil organisms[50], which may in part be lost through intensive tillage.

The Chazy site showed the highest difference in OM from tillage systems (average of 46% higher OM in NT compared to PT after 31+ years; Table 3), presumably due to the longer duration of this trial. Tillage and cover crop effects on OM were not significant at the Geneva site for both rotations (Table 4), suggesting that it takes a longer period of time before such effects are discernable. Some previous studies have shown that there is generally no significant difference in OM content between NT and PT for up to about 10 years after treatment application[51,52]. The extent of the OM accumulation as a function of tillage and cover cropping may depend on soil type, climate and the extent of previous soil degradation.

The AC test has been proposed as a measure of soil quality, capable of detecting changes in the labile soil organic carbon pool[25]. AC has been shown to correlate with water-stable aggregates and some other biological measurements such as soluble carbohydrate, microbial biomass, and basal and substrate-induced respiration[25]. AC was significant for tillage effect at the Willsboro site in 2004 and at

the Aurora site in 2007 (Table 2). At Chazy, AC was significant for both the tillage and the harvest method treatments (Table 3). Where significant differences were detected: the NT treatment had higher AC than the PT treatment and COG had higher AC than the COS treatment (Tables 2 and 3). Generally, AC as a soil quality indicator was similar to the OM in the long-term trials at Chazy, Willsboro and Aurora. For the relatively short-term Geneva experiment, AC measurement did not give a clear indication of the direction of better management practices, i.e., NT had lower AC than PT and vetch cover had lower AC than no cover treatment. Generally for all the sites, AC as a soil quality indicator did not provide additional information to OM.

The PMN measurement reflects the nitrogen cycling potential of the soil and serves to assess the rate at which soil microbes make nitrogen available from the soil OM[26]. PMN was significant with tillage effect in 2004 at the Willsboro and Chazy sites (Tables 2 and 3), but not in 2007. In Aurora, PMN was not significant during both years (Table 2). Generally, PMN values were higher in NT compared to PT treatments. PMN was significant with tillage and cover crop treatments at the Gates Farm under R1, but not under R2 (Table 4). In R1, PMN was significantly higher in the ZT treatment than the NT and PT treatments, while vetch cover crop had significantly higher PMN than rye cover crop and the no-cover treatments. This suggests that the PMN is not strongly affected by long-term management practices as some other soil quality indicators, and response is site dependent and affected by the utilization of organic N sources such as leguminous cover crops.

The RDP were generally low (<4) at Willsboro, Aurora and Chazy, which are field crops sites (Tables 2 and 3). A lower score indicates healthier roots. In Geneva, with a vegetable rotation trial, the RDPs were greater than 4.8, indicating a higher susceptibility of vegetable systems to root-borne pathogens (Table 4). This result was expected because the crop used for the root bio-assay [snap bean (*P. vulgaris* L.)] is highly susceptible to the prevalent root rot pathogens of vegetables in the Northeast region (*Fusarium solani* f. sp. *phaseoli*, *Rhizoctonia solani*, *Pythium ultimum* and *Thielaviopsis basicola*) and the lesion nematode (*Pratylenchus* spp.) individually or in any possible combination[53]. Therefore, the snap bean root assay serves as a more relevant soil quality indicator in vegetable systems.

Soil chemical indicators

The soils at the different sites were chemically managed according to the Cornell guidelines[54]. Although some treatment effects were significant for a number of the chemical indicators (pH, P, K, Mg, Fe, Mn and Zn), depending on site and year of measurement (Tables 2–4), most of the results were generally within the optimal ranges for crop production in New York. K levels, however, vary with sites and management practices. The K levels were very high at the Willsboro clay loam site, while the silt loam sites of Aurora and Chazy had low to medium K levels (Tables 2 and 3). The Gates Farm site had medium to high K levels (Table 4). At the Chazy site, there was a significantly lower K level in COS compared to COG treatment (Table 3). The K level was about 42% less in COS treatment compared to COG (Table 3). The COS treatment with stover removed led to a depletion in the soil K due to the lack of additional OM in the form of plant residue. The level of soil K was low for COS treatment and medium for the COG treatment, suggesting that a higher rate of K fertilizer is needed to correct K deficiency in the plots with stover removed. The samples used for this study were collected in the early spring just before the planting season. The experimental plots at all sites normally receive fertilizer applications based on soil test results to supplement the soil nutrients for optimal crop production. The generally higher pH (>7) of the silt loam soils in Aurora, Chazy and Gates Farm (Tables 2–4) reflect the calcareous nature of the parent materials on which they were formed.

CSHI

The CSHT was developed to integrate soil indicator measurements and to highlight soil functions with constraints[10,21]. Another attraction offered by indexing soil indicator measurements lies in the ability to make a judgment about the overall quality of the soil. The CSHI showed significant tillage effects at the Willsboro ($P<0.1$), Aurora ($P<0.01$) and Chazy ($P<0.01$) sites (Tables 2 and 3). At the Geneva site, the CSHI showed significant tillage effect for R1 but not for R2 (Table 4). CSHI was significant for the harvest method at Chazy ($P<0.01$) but not for cover crops at the Geneva site (Tables 3 and 4). The performance of the CSHT in differentiating better management practices at these sites shows its potential to serve as a tool for directional soil quality measurement. Although the Geneva site had relatively short duration of treatment applications, the CSHI was able to show that the reduced tillage practices were moving soil quality in a positive direction (Table 4).

Comparing the Willsboro to the Aurora site, which had the same management history, the CSHI for NT was 71.1% for Willsboro and 60.6% for Aurora, and for the PT treatment, it was 58.9 and 48.3% at each location, respectively. The same management practices in different soil therefore yielded the same magnitude of soil quality improvement from reduced tillage as reflected by the CSHI (12.2% for Willsboro and 12.3% for Aurora).

PCA

Figures 1–3 show different groupings exhibited by the treatments at Chazy, Willsboro and Aurora. The PCA groupings on factor plane 1 versus factor plane 2 at Chazy show a separation into two distinct classes based primarily on tillage treatment (Fig. 1). The harvesting method treatments did not show as distinct a grouping. This suggests that the tillage effect was more dominant at Chazy than the

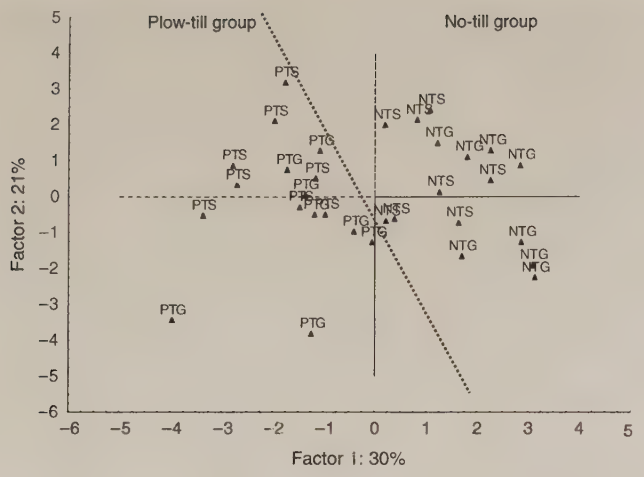

Figure 1. PCA groupings on factor plane 1 versus factor plane 2 for Chazy tillage trial. PTG, plow-till grain; PTS, plow-till silage; NTG, no-till grain; NTS, no-till silage.

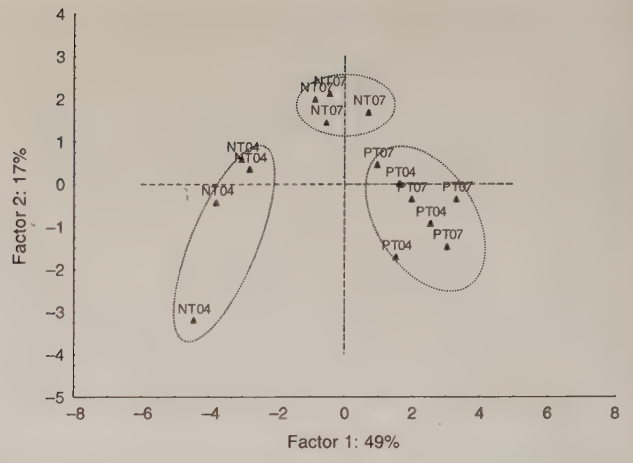

Figure 2. PCA groupings on factor plane 1 versus factor plane 2 for Willsboro tillage trial. PT04, plow-till 2004; PT07, plow-till 2007; NT04, no-till 2004; NT07, no-till 2007.

harvest treatment effects, as confirmed by the ANOVA results (Table 3). The *P* levels for many of the soil health indicators were lower for tillage effects compared to the harvest method effects. At Chazy, the soil indicators with high loadings (>0.7 or < −0.7) were WAS, OM, AC and pH on factor plane 1 and only Mn on factor plane 2. Similarly, at the Willsboro site, the PCA groupings on factor plane 1 versus factor plane 2 were also according to tillage (Fig. 2), although the NT treatments for 2004 grouped differently from the NT for 2007. The PT treatments for 2004 and 2007 clustered together (Fig. 2). At Willsboro, the soil indicators with high loadings (>0.7 or <−0.7) were WAS, OM, AC, PMN, pH, P and Zn on the factor plane 1 and Mn and Fe on the factor plane 2. For the Aurora site, NT and PT treatments grouped separately and the 2004 and 2007 results for both tillage treatments were also separated in the factor space (Fig. 3). At Aurora, OM, P, K and Fe had high loadings (>0.7 or <−0.7) on factor plane 1, while only pH had high loading on factor plane 2.

The PCA results from both the Willsboro and Aurora sites confirm the observations made at Chazy about the significance of tillage in affecting the soil quality. Further separation of the treatments according to different years for the Aurora and Willsboro sites may be due to several factors including differences in sample handling (disturbed versus undisturbed cores) and weather patterns for both years.

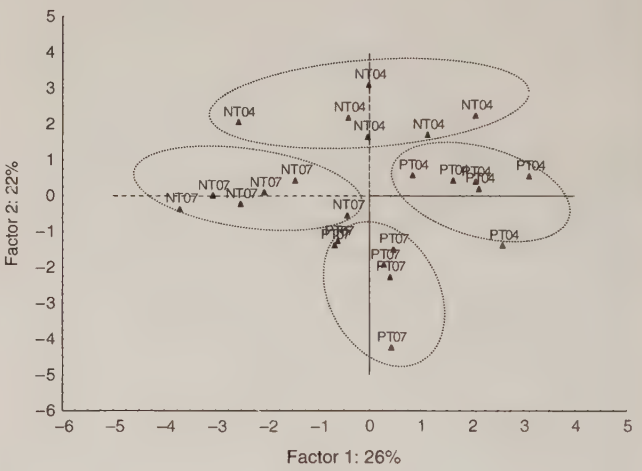

Figure 3. PCA groupings on factor plane 1 versus factor plane 2 for Aurora tillage trial. PT04, plow-till 2004; PT07, plow-till 2007; NT04, no-till 2004; NT07, no-till 2007.

Conclusions

A study was conducted to evaluate soil quality indicators in four long-term experimental trials in New York State. The indicators that were assessed are currently being used for the recently developed CSHT, a commercially available soil quality test.

Indicators that showed significant treatment differences were dependent on the site/soil type, treatment factors and the duration of treatment applications. Tillage effects gave a very strong contrast for many of the significant indicators. The reduced tillage treatments generally had more favorable values for soil indicators than the continuous PT systems. The magnitude of the differences between the PT and the NT treatments for some of the indicators was dependent on soil type and duration of treatment application. Also, WAS benefited more from the reduced tillage (NT) than from the residue addition at the Chazy site. Generally across all sites, WAS, OM and AC were most sensitive to treatment effects and PMN and RDP were more site and management dependent. The chemical indicators were minimally affected by soil management practices and generally, their levels were not constraining for crop production in New York. Stover removal, however, resulted in reduced soil K levels. The CSHI that integrates all the indicator measurement into a single index value proved very sensitive to the integrative effects of the different

treatments, with the NT treatments having higher index values than the PT, and stover return having higher values than stover removed.

Overall, we conclude that soil management effects are significant for several soil quality indicators that are used in the CSHT, but others are less impacted. The composite analysis, however, provides a good evaluation of a soil's quality.

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Sorghum sudangrass as a summer cover and hay crop for organic fall cabbage production

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Abstract

No-tillage (NT) organic vegetable production presents several economic opportunities for growers in the southeastern United States while promoting natural resource conservation. This study was conducted to determine if removal of sorghum sudangrass (SS) cover crop biomass as hay, frequency at which the cover crop is mowed, and tillage affect weed suppression and head weight of transplanted organic cabbage. Sorghum sudangrass [*Sorghum bicolor* (L.) Moench × *Sorgum sudanense* (Piper) Staph.] was planted in May 2004 at Reidsville and Goldsboro, NC, preceding the planting of organic 'Bravo' cabbage (*Brassica oleracea* L. Capitata group) in August and September 2004, respectively. SS management systems included: low-frequency mowing with hay removed following the first mowing operation (LFM-H), low-frequency mowing with hay not removed (LFM), high-frequency mowing with hay not removed (HFM) and a no cover crop control. Two tillage treatments were applied within each management system: conventional tillage (CT) and NT. Under NT conditions, SS mulch generated by LFM offered broadleaf weed control in cabbage similar to that achieved under CT, regardless of whether cover crop biomass was removed as hay. Mowing with higher frequency reduced SS cover crop biomass by 18–33% and reduced weed suppression in NT cabbage. Mowing frequency did not influence the quantity of SS that re-grew in the cabbage crop. SS re-growth contributed to lower head weight in NT compared to CT cabbage in Goldsboro, and crop failure of NT cabbage in Reidsville. Cabbage head weight was highest when the crop was not preceded by SS in both CT and NT systems (1.6 as opposed to 1.3–1.4 kg head^{-1}). Our findings suggest that the potential for growers to manage a cover crop also as a hay crop does exist; however, SS may not be a compatible cover crop species for organic fall cabbage production due to high amounts of re-growth.

Key words: *Sorghum bicolor* × *Sorghum sudanense*, *Brassica oleracea*, no-tillage, conservation tillage, organic vegetable production, cover cropping, weed management

Introduction

No-tillage (NT) production systems are recognized as a means of reducing soil erosion, conserving soil water, promoting more efficient use of labor and machinery, and decreasing or eliminating the need for chemical inputs such as pesticides[1,2]. Though the majority of acreage currently under NT is in row crop production, studies suggest that NT practices can also be advantageous in vegetable production[3–5]. Given that consumer demand for organic foods has grown consistently between 15 and 20% annually since 1997[6], the development of NT organic vegetable production systems will support growers seeking to optimize both biological and economic productivity.

A common feature of NT systems is the incorporation of cover crops. Cover crops have been shown to reduce soil erosion[7], limit runoff and surface water pollution[8], improve soil physical properties[9], and influence soil fertility by providing a source of N for subsequent crops[10] and capturing soil mineral N to prevent loss to leaching[11]. Many cover crops also have the capacity to suppress weeds[12,13], disrupt pest and disease cycles[14], and suppress nematode populations[15,16], providing alternative strategies to chemical inputs for pest management in organic systems. A

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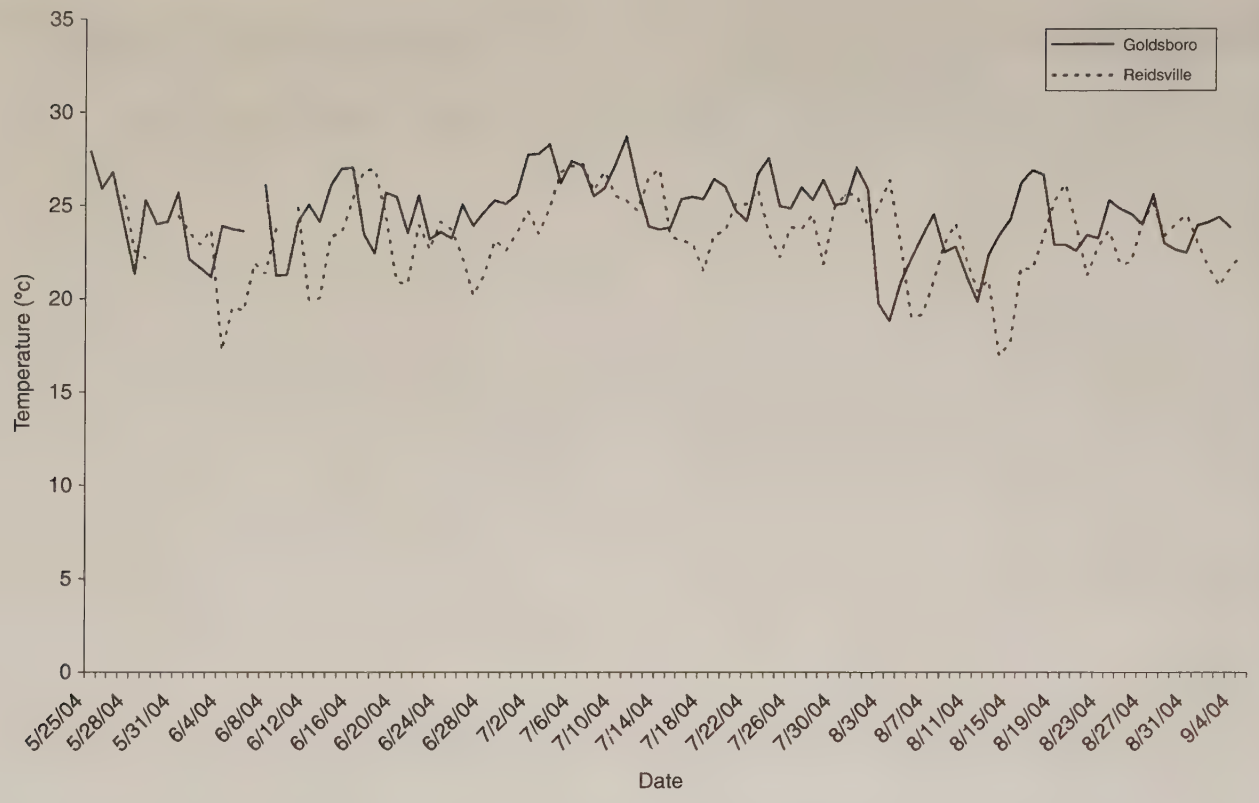

Figure 1. Average daily air temperature from 25 May to 7 September 2004, at Goldsboro and Reidsville, NC.

significant impediment to organic NT vegetable production is the effectiveness of mechanical strategies to kill cover crops prior to cash crop production.

In the southeastern United States, summer annual cover crops may be rotated between spring and fall production seasons in NT vegetables. In a study by Abdul-Baki et al.[3], comparable yields of fall broccoli were achieved between a conventional tillage (CT) system and an NT system utilizing mulches of forage soybean and foxtail millet that had been killed by flail mowing. Morse[17] examined the potential of foxtail millet, soybean and cowpea cover crops in monoculture and grass–legume bi-culture to provide weed suppression and sufficient N for organically grown fall broccoli. This study found that yields were higher under NT cover crop mulch compared to NT bare soil; however, both N and weed management were yield limiting in organic broccoli. The cover crop species were successfully killed by rolling and flail mowing.

Another potential summer cover crop for organic NT vegetable production is sorghum sudangrass (SS). As a cover crop, this species has the potential to produce abundant biomass[18], suppress weeds through physical and chemical interference[18,19] and decrease soil compaction[20]. Creamer and Dabney[21] reported that SS is difficult to kill using mechanical methods such as mowing, undercutting and rolling, a potential drawback to its inclusion in rotation with NT organic vegetables. As a commonly cultivated forage crop for grazing, hay or silage[22], the species also presents the opportunity for dual application as both cover crop and hay crop.

Growing consumer demand for organic meat, eggs and dairy products has led to increased demand for organic hay, which typically garners a premium of 10–20%. Incorporating a cover crop such as SS that can be harvested and sold on the organic hay market may provide an economic benefit to growers.

The objectives of this study were:

1. To assess the impact of removing a single cutting of SS biomass for hay on its weed suppressive qualities in CT and NT fall vegetable production.
2. To determine if increasing cutting frequency can improve SS response to mechanical kill by mowing.
3. To examine the production risks introduced by a SS cover crop grown immediately before a cash crop.

Materials and Methods

Field experiments were conducted in 2004 at two locations: the Center for Environmental Farming Systems (CEFS) in Goldsboro, North Carolina and the Upper Piedmont Research Station (UPRS) in Reidsville, North Carolina. While it can be viewed as preferable to perform the same experiment during two separate years at the same site to take advantage of weather variability, rainfall and temperature differences between the two experimental locations (Fig. 1 and Table 1) were greater than they may have been

Table 1. Rainfall totals (cm) from 16 May to 30 September 2004 in Goldsboro and Reidsville, NC.

Date	Goldsboro	Reidsville
16–31 May	3.1	1.7
1–15 June	8.0	8.7
16–30 June	14.0	5.2
1–15 July	1.8	2.8
16–31 July	4.5	8.2
1–15 August	12.3	7.2
16–31 August	6.2	3.7
1–15 September	3.2	7.5
16–30 September	3.4	8.3
Season total	56.5	53.3

at the same site over 2 years. The sites are approximately 240 km apart and located in two distinct ecoregions of North Carolina. At Goldsboro, the experiment was conducted on Wickham loamy sand, a thermic Typic Hapludult, with 0–2% slope (WhA), and in Reidsville, on Vance sandy loam, also a thermic Typic Hapludult, with 0–2% slope (VaB).

Experimental design

At each location, this experiment employed a split-plot experimental design with whole plots in four replicates in a Latin Square arrangement. SS cover crop management treatments served as the main plots and tillage treatment as the split plots. After an initial mowing operation was performed uniformly in all plots, three SS management treatments were applied: (1) hay biomass removed from the field, subsequent low-frequency mowing (LFM-H); (2) hay biomass left in the field, subsequent low-frequency mowing (LFM); (3) hay biomass left in the field, subsequent high-frequency mowing (HFM). Treatment four was a no cover crop control (NO) (Table 2).

Cover crop management

On 25 and 27 May 2004, 4 × 6 m (12.75 × 20 ft) plots were established in Goldsboro and Reidsville, respectively. Prior to planting, 112 kg N ha^{-1} (100 lb A^{-1}) as soybean meal and 2.2 kg B ha^{-1} (2 lb A^{-1}) were broadcast and incorporated at each field site. Untreated SS 'Haychow' (Hall Seedway, Hall, NY) was seeded at a rate of 35 kg ha^{-1} (40 lb A^{-1}) using a Sukup drill (Sukup Manufacturing Company, Sheffield, IA) in Goldsboro and Bush Hog® 7690 drill (Bush Hog®, LLC, Selma, AL) in Reidsville. At 36 (Goldsboro) and 40 (Reidsville) days after planting, the crop had reached a height of 1.2–1.5 m, and the first mowing operation was conducted using a flail mower. SS clippings were removed from LFM-H plots using hand rakes to simulate removal of cover crop biomass as hay. The stubble height was 7.5–10.0 cm (3–4 in) for the first cutting operation to encourage re-growth. Stubble height in all subsequent mowing events, also performed with a flail mower, was 2.5–5.0 cm (1–2 in). Additional cutting operations in each plot were conducted each time the crop again reached a height of 1.2–1.5 m in both LFM treatments or a height of 0.6 m in HFM plots (Table 2).

Prior to transplanting fall cabbage, each whole plot was split into two sub-plots: CT and NT. CT sub-plots were mowed for the final time approximately 2 weeks before transplanting fall cabbage and tilled twice with a rototiller before transplanting in order to incorporate SS residues. CT sub-plots in the control treatment were subject to the same tillage regime. Emerged weeds were removed from CT sub-plots immediately prior to the transplanting operation by flame weeding (Goldsboro) or tillage (Reidsville). NT sub-plots were mowed with a flail mower to a stubble height of 2.5–5.0 cm immediately prior to the transplanting operation. In addition, glyphosate (N-phosphonomethyl glycine) was applied to NT sub-plots in the control treatment 2 weeks prior to transplanting in order to eliminate weeds that had emerged during the summer without disturbing the soil prior to the application of wheat straw mulch. This control was designed to differentiate effects of tillage from those of SS residues on weed suppression and was not intended to provide evaluation of organic weed management. For experimental purposes, it was necessary to begin the comparison of tillage and SS residues in sub-plots free of existing summer weeds, and glyphosate was considered an appropriate research tool to achieve these conditions. Wheat straw mulch was applied to the NT control immediately following cabbage transplanting at a rate equal to the total SS biomass produced in LFM treatment plots. Though known to contain allelochemicals, no detrimental effects of wheat straw mulch on transplanted vegetables have been reported[23] and in previous studies wheat straw mulch on transplanted tomatoes did not reduce yield when surface applied[24,25].

Cabbage planting

Cabbage (cv. Bravo) transplants were set by hand on 9 August 2004 in Reidsville and using a sub-surface tiller transplanter (S-STT) on 3 September 2004 in Goldsboro. Cabbage was used as a test crop to determine production potential and examine possible negative impacts of SS and tillage management on crop development. Each sub-plot contained a single row of cabbage 6 m in length with an in-row spacing of 35 cm (16 plants $plot^{-1}$). An Organic Materials Review Institute (OMRI)-reviewed 4-2-4 fertilizer (Fertrell Feed-N-Gro, Bainbridge, PA) was applied at the recommended rate of 2800 kg ha^{-1} (2500 lb A^{-1}) at transplanting to provide 112 kg N ha^{-1} (100 lbs N A^{-1}). Stand counts were recorded for each sub-plot at 1 and 2 weeks after transplanting (WAT) cabbage, and missing and dead plants were replaced. Pest management included weekly applications of capsaicin [commercially available as Miller Hot Sauce (Miller Chemical, Hanover, PA)] during the first 5 weeks of growth to deter mammalian pests. Xentari (*Bacillus thuringiensis*) was applied as needed

Table 2. Sorghum sudangrass (SS) management treatments applied at Goldsboro and Reidsville, NC in 2004.

Location	SS treatment[1]	Initial cutting height (m)	Hay removed	Mowing frequency	Subsequent cutting height (m)	Number of cuts in season	NT mulch
Goldsboro	LFM-H	1.2–1.5	Yes	Low	1.2–1.5	3	SS
	LFM	1.2–1.5	No	Low	1.2–1.5	3	SS
	HFM	1.2–1.5	No	High	0.6	4 to 5[2]	SS
	NO	–	–	–	–	–	Wheat straw
Reidsville	LFM-H	1.2–1.5	Yes	Low	1.2–1.5	2	SS
	LFM	1.2–1.5	No	Low	1.2–1.5	2	SS
	HFM	1.2–1.5	No	High	0.6	3 to 4[3]	SS
	NO	–	–	–	–	–	Wheat straw

[1] LMF-H, low-frequency mowing, hay removed; LFM, low-frequency mowing, hay not removed; HFM, high-frequency mowing, hay not removed; NO, no SS cover crop.
[2] In Goldsboro, tilled sub-plots were cut 4 times and NT sub-plots were cut 5 times due to 2-week difference in time of final kill.
[3] In Reidsville, tilled sub-plots were cut 3 times and NT sub-plots were cut 4 times due to 2-week difference in time of final kill.

based on weekly scouting for lepidopteran pests. Four weeks after planting, plants were side-dressed with 22 kg N ha^{-1} (20 lb A^{-1}) as sodium nitrate (SQM North America, Atlanta, GA). Use of irrigation systems at each location (a drip system in Goldsboro and an overhead system in Reidsville) ensured that plants received adequate moisture at planting and 2.5 cm (1 in) water weekly if rainfall was inadequate. CT sub-plots were cultivated 3 and 6 WAT. NT sub-plots were not mowed or cultivated during the cabbage-growing season.

Cover crop biomass

Prior to each SS mowing event, SS cover crop and weed biomass were sampled in all sub-plots. Using a randomly placed 0.5 m^2 quadrat, two samples per plot were cut with hand clippers to the same stubble height as prescribed for the mowing operation and biomass sorted into cover crop, broadleaf weeds and grass/sedge weeds. After drying samples at 70°C for at least 48 h, dry weights were recorded.

Soil moisture, inorganic N and bulk density

All sub-plots were sampled for gravimetric soil moisture and inorganic N on three dates during the cabbage growing season: 2 WAT, 2 weeks after sodium nitrate application (6 WAT) and at harvest. Six 15-cm deep cores were collected from each sub-plot using a 2-cm diameter soil probe and mixed to create a composite sample for each sub-plot on each sample date. To determine the percent moisture on a dry weight basis, a sub-sample was oven dried for 24 h at 105°C. Samples for inorganic N analysis were frozen at < 5°C until processing. After air-drying in a greenhouse, soil samples were ground to pass through a 16-mm screen. Five grams of ground soil were extracted with 50 ml 2 M KCl. Using injection flow analysis (Lachat Instruments, Milwaukee, WI), extracts were colormetrically analyzed for NH_4- and NO_3-N. Reported values for total inorganic N represent the sum of NH_4- and NO_3-N. Bulk density was measured in CT and NT sub-plots of the LFM treatment at 6 WAT. An Uhland drive tube was used to collect soil samples using a 347.5 cm^3 cylinder. Each cylinder with soil was weighed, dried at 105°C for 48 h, and weighed again to calculate bulk density.

Weed biomass in transplanted cabbage

Prior to mechanically weeding CT sub-plots at 3 and 6 WAT and at cabbage harvest (12 WAT), weed and SS re-growth biomass was sampled. Using a 0.25 m^2 quadrat two biomass samples were cut with hand clippers from all CT and NT sub-plots. The quadrat was placed randomly along the length of the row and centered on the cabbage. Weed and re-growth biomass was sorted, dried and weighed following the procedure used for cover crop biomass.

Cabbage harvest

Cabbage harvest was performed at ten-day intervals beginning on 1 November and 19 November in Reidsville and Goldsboro, respectively. We attempted to harvest heads weighing 1.0 kg as marketable heads; however, for final classification purposes, marketable heads included all heads weighing 0.5 kg or more. The six outermost heads (three at each row end) in each sub-plot were considered guard plants and not included in harvest statistics; the maximum number of heads that could be harvested from each sub-plot was ten. At harvest, each head and four wrapper leaves were cut and weighed. Thirty days after the first harvest, plants that had not produced a head or which had a head weighing less than 0.5 kg (categorized as 'culls') were harvested. Whole plants were cut and weighed to determine the fresh weight. The number of dead plants per sub-plot was determined by subtracting the sum of marketable heads plus culls from 10.

Table 3. Cumulative biomass of SS cover crop (including biomass removed as hay) produced prior to final mowing (2 September 2004 in Goldsboro and 9 August 2004 in Reidsville) and biomass of SS that re-grew in NT sub-plots during the cabbage season as determined at the time of cabbage harvest (19 November 2004 in Goldsboro and 1 November 2004 in Reidsville) in Goldsboro and Reidsville, NC.

	Goldsboro		Reidsville	
SS management	SS cover crop biomass ($t\,ha^{-1}$)	SS re-growth biomass ($t\,ha^{-1}$)	SS cover crop biomass ($t\,ha^{-1}$)	SS re-growth biomass ($t\,ha^{-1}$)
LFM-H	14.4a[1]	0.7	8.0ab[2]	8.5
LFM	14.0a	1.6	9.9a	10.7
HFM	11.5b	1.5	6.7b	9.9

[1] Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$.
[2] Data on accumulated SS biomass in Reidsville were transformed to square root (x) before analysis. Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$. Means were back transformed for presentation.

Statistical analysis

Analysis of variance was performed using Proc GLM in SAS[26]. A combined analysis with data from both sites was carried out, followed by separate analyses for each location due to strong location by treatment interaction. The effect of SS management (treatment) was tested against whole-plot error (obtained after removing block, column and treatment effects). When a significant interaction occurred between whole-plot (SS management) and split-plot (tillage) effects, treatment means were compared at each tillage level. Mean separation was carried out using Fisher's least significant difference (LSD)[27]. Biomass values were square- or log-transformed before analysis where necessary to reduce variance heterogeneity. Proc Corr[26] was used to determine correlations between weed biomass and SS residue biomass and cabbage head weight and SS residue biomass at both locations, and cabbage head weight and SS re-growth biomass at Goldsboro[27].

Results and Discussion

SS cover crop biomass

SS cover crop biomass at the first mowing, an estimate of hay yield, was $8.0\,t\,ha^{-1}$ in Goldsboro and $5.7\,t\,ha^{-1}$ in Reidsville. Low mean daily temperature (Fig. 1) and wide row spacing may have led to lower hay yield in Reidsville. Frequency of mowing impacted SS cover crop biomass production during the summer season (Table 3). In Goldsboro, cumulative SS cover crop biomass was lower under the HFM treatment ($11.5\,t\,ha^{-1}$) than the LFM treatment [$14.4\,t\,ha^{-1}$ when hay was removed (LFM-H) and $14.0\,t\,ha^{-1}$ when hay was not removed (LFM)]. In Reidsville, SS cover crop biomass was lower in HFM plots ($6.7\,t\,ha^{-1}$) than in LFM plots ($9.9\,t\,ha^{-1}$). The inverse relationship observed between cutting frequency and biomass production was previously demonstrated by Beuerlein et al.[28] SS cover crop biomass production was not compared between CT and NT sub-plots because the time of final mowing varied by tillage treatment.

SS re-growth biomass

SS re-growth following cabbage transplanting occurred in NT sub-plots at both locations. In Goldsboro, $0.7–1.6\,t\,ha^{-1}$ of SS re-grew during the cabbage season (Table 3). SS re-growth biomass in Reidsville was 5–11 times higher ($8.5–10.7\,t\,ha^{-1}$) than in Goldsboro (Table 3). SS re-growth was observed to have begun in Reidsville by 3 WAT, but was delayed in Goldsboro. The final cutting and transplanting in Goldsboro occurred on 3 September 2004, following a month of significant rainfall that totaled 18.5 cm (Table 1). Wet field conditions at the time of mowing and transplanting operations may have led to soil compaction by machinery, one possible cause of SS failure to tiller immediately in Goldsboro. The biomass of SS re-growth did not vary by management system (Table 3), indicating that neither residue removal nor mowing frequency influenced re-growth. Because increased mowing frequency was not an effective means of reducing SS re-growth, SS represented a significant competitor with the subsequent cabbage crop under NT management at both locations.

Weed biomass in transplanted cabbage

Weed biomass trends in transplanted cabbage were similar across sampling dates at both locations; results obtained from analysis of variance are presented only for data collected at 6 WAT.

At Goldsboro, cover crop treatment influenced broadleaf weed biomass in NT cabbage (Table 4). Winter annual weeds including henbit (*Lamium amplexicaule* L.), purslane speedwell (*Veronica peregrina* L.) and common chickweed [*Stellaria media* (L.) Vill.] accounted for 70, 10 and 10%, respectively, of the density of broadleaf weeds identified in NT sub-plots at 6 WAT. Broadleaf weed biomass was greater under the HFM treatment ($0.76\,t\,ha^{-2}$) than the LFM treatment ($0.18\,t\,ha^{-2}$; Table 4). LFM led to greater SS cover crop biomass (Table 3) and, subsequently, more biomass returned to the soil surface as mulch. Mohler and Teasdale[29] concluded that increasing mulch (cover crop residue) biomass can reduce the emergence of many

Table 4. Effects of SS management and tillage on weed biomass in transplanted cabbage at 6 WAT in Goldsboro, NC in 2004.

		Weed biomass ($t\,ha^{-2}$)		
Tillage	SS management	Broadleaf	Grass/sedge[2]	Total[3]
NT	LFM-H	0.07b[1]	0.00	0.56a[1]
	LFM	0.18b	0.00	0.39a
	HFM	0.76a	0.14	1.05a
	Wheat straw mulch	0.01c	0.00	0.01b
Conventional	LFM-H	0.08	0.00	0.08
	LFM	0.08	0.00	0.08
	HFM	0.05	0.01	0.09
	No SS	0.11	0.02	0.13

[1] Data were transformed to $\log(x+0.00005)$ before analysis. Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$. Means were back transformed for presentation.
[2] Data on grass/sedge weed biomass in Goldsboro were not subject to analysis of variance due to a low number of sub-plots that contained grass and sedge weeds.
[3] Total weed biomass represents the sum of broadleaf, grass/sedge and SS re-growth.

Table 5. Effect of SS management (averaging over tillage methods) on SS biomass returned to soil surface as mulch in NT cabbage and SS biomass cut at the final mowing operation in NT cabbage at Goldsboro, NC in 2004.

SS management	SS biomass returned ($t\,ha^{-1}$)	SS biomass of final mow ($t\,ha^{-1}$)
LFM-H	7.9c[1]	2.4a
LFM	15.0a	3.1a
HFM	11.7b	0.2b

[1] Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$.

Table 6. Main effects of SS management and tillage on cabbage survival, head size, and maturity at Goldsboro, NC in 2004.

	No. of heads harvested[1]	Average head size (kg)	No. of heads 1st harvest
SS management			
LFM-H	9.0	1.3b[2]	5.6
LFM	9.3	1.3b	5.6
HFM	8.6	1.4b	5.6
No SS, wheat straw mulch	10.0	1.6a	7.1
Tillage			
NT	8.4b[2]	1.1b	3.2b
Conventional	10.0a	1.7a	8.8a

[1] Maximum number of heads harvested in each sub-plot equals 10.
[2] Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$.

weed species. In addition, residue particles generated from HFM were younger when cut and had a lower C : N ratio than those generated from LFM[30]. These characteristics can reduce weed suppression by cover crop mulch due to shorter residue longevity and inadequate soil surface coverage. Our results suggest that frequently mowing SS reduces weed suppression by the cover crop mulch.

Under NT conditions at Goldsboro, wheat straw mulch offered the greatest broadleaf weed suppression. Weed suppression was likely improved due to even distribution of the mulch by hand. In addition, the application of glyphosate to the NT control that preceded the final pre-transplant mowing operation eliminated weeds of a size that may have escaped mowing in NT treatment sub-plots.

In NT plots at Goldsboro, SS cover crop biomass returned to the soil surface as mulch was lowest when hay was removed ($7.9\,t\,h^{-1}$; Table 5). The quantity of biomass applied as mulch was derived by subtracting the biomass of hay harvested at the time of the first cutting from the cumulative SS cover crop biomass produced prior to cabbage planting. Despite resulting in a smaller quantity of mulch accumulated prior to cabbage transplanting, hay removal followed by LFM led to broadleaf weed suppression equal to that achieved with LFM alone and better than that achieved with HFM under NT conditions (Table 4). This is attributed to characteristics of the residues generated by HFM previously discussed, specifically smaller size and lower C : N ratio than residues generated from LFM. There was a negative correlation ($R = -0.59$; $P = 0.042$) between SS biomass at the final mowing event (Table 5) and broadleaf weed biomass at 6 WAT, indicating that as the quantity of residue deposited immediately prior to cabbage transplanting increased, appearance of broadleaf weeds in the cabbage crop decreased. Because hay removal did not impact the quantity of SS cover crop biomass cut at the end of season, removal of SS hay biomass early in the season did not reduce weed suppressive qualities of the SS cover crop. Overall, removal of SS as hay following the first mowing operation did not reduce weed suppressive qualities of the SS cover crop when it was subsequently mowed with low frequency, which allowed the crop to re-grow to 1.2–1.5 m.

The impact of tillage on weed suppression by SS under LFM was assessed for broadleaf weeds in Goldsboro. Analysis of variance indicated that SS cover crop biomass generated under LFM, regardless of hay removal strategy, resulted in the same level of broadleaf weed suppression in CT and NT cabbage ($P = 0.647$). The results of this study suggest that in an organic production system, sufficient levels of NT SS cover crop residue may provide weed control of annual broadleaf weeds comparable to tilled SS residue plus cultivation. Grass and sedge weed populations were too low to analyze at this location.

Table 7. Effects of SS management and tillage on cabbage survival, head size and maturity at Reidsville, NC in 2004.

Tillage	SS management	No. of heads harvested[1]	Average head size (kg)	No. of heads 1st harvest
NT	LFM-H	0	–	–
	LFM	0	–	–
	HFM	0	–	–
	Wheat straw mulch	9.3	1.4	4.8
Conventional	LFM-H	9.8	1.5ab[2]	6.8
	LFM	9.3	1.3b	5.3
	HFM	9.8	1.6ab	8.8
	No SS	8.8	1.9a	6.5

[1] Maximum number of heads harvested in each sub-plot equals 10.
[2] Mean separation within columns by Fisher's LSD test at $P \leqslant 0.05$.

Table 8. Main effect of tillage on gravimetric soil water and soil inorganic N on three dates in the cabbage growing season in Goldsboro and Reidsville, NC in 2004.

	% Water						Soil inorganic N (μg N g soil^{-1})					
	Goldsboro			Reidsville			Goldsboro			Reidsville		
Tillage	16-Sep	18-Oct	19-Nov	23-Aug[2]	22-Sep	22-Nov	16-Sep	18-Oct	19-Nov	23-Aug	22-Sep	22-Nov
NT	20.0a[1]	17.8a	19.0a	20.2	17.5a	18.5a	66.9	28.8	8.9	44.4b[1]	11.8	6.8
Conventional	17.9b	17.0b	18.5b	16.5	14.0b	16.3b	74.7	31.8	9.6	74.2a	15.3	6.0

[1] Mean separation within columns by Fisher's significant difference test at $P \leqslant 0.05$.
[2] Mean separation not presented for main effect of tillage due to significant treatment by tillage interaction ($P = 0.001$) on this sampling date.

Results regarding broadleaf and grass/sedge weed suppression in Reidsville are confounded by the high level of SS re-growth in NT cabbage (Table 3). The SS re-growth behaved like a weed and contributed to cabbage crop failure. Grass and sedge weed biomass in CT cabbage (0.03 t ha^{-2}) was significantly ($P = 0.015$) lower than in NT cabbage (0.25 t ha^{-2}), suggesting that the NT system did not provide adequate control of grasses and sedges. We attribute this result to the fact that the perennial species yellow nutsedge (*Cyperus esculentus* L.) represented an average of 55% of the grass and sedge weed population by number on all three sampling dates in Reidsville. Other species present in the cabbage crop were summer annual grasses including smooth crabgrass (*Digitaria ischaemum* Schreb. Ex. Muhl.), goosegrass [*Eleusine indica* (L.) Gaertn.)], fall panicum (*Panicum dichotomiflorum* Michx.) and broadleaf signal grass [*Urochloa platyphylla* (Munro ex Wright) R. Webster]. These species had also been present in the growing cover crop. Previous work has concluded that NT systems employing cover crops have the highest weed pressure from perennial species[31]. Our results support this conclusion and offer further evidence that mechanical cultivation may provide better control of perennial species and established annual grasses than NT management.

Effects of tillage on cabbage survival, head weight and maturity

At Goldsboro, cabbage survival, head weight and the number of heads collected on the first harvest date were greater with CT than NT (Table 6). There was a negative correlation between head weight and SS re-growth biomass ($R = -0.72$; $P < 0.001$), as well as between the number of heads harvested on the first harvest date and re-growth biomass ($R = -0.78$; $P < 0.001$), suggesting that SS re-growth in NT sub-plots exhibited competition with the cabbage crop. NT production at Reidsville resulted in a crop failure in SS residues (Table 7). Early onset of SS re-growth and biomass production nearly equal to that in the cover crop only system suggest that resource competition with SS contributed to cabbage failure.

Environmental differences between CT and NT sub-plots may have contributed to cabbage growth reduction in NT production in Goldsboro. NT systems typically exhibit higher soil moisture levels than CT systems[2]. Though soil moisture was significantly higher in NT soils on all sampling dates (Table 8), it was not likely that this difference was agronomically significant. NT systems also influence soil nutrient availability[2]. The fertilizer application method, rate and timing were intended to eliminate

variation in inorganic N availability due to tillage or cover crop management. The concentration of soil inorganic N did not vary between CT and NT sub-plots throughout the season in Goldsboro (Table 8), suggesting that N availability did not limit cabbage growth in NT sub-plots. Soil compaction has also been posited as a yield limiting factor in previous studies in which NT production resulted in lower cabbage yield[32,33]. Field studies have demonstrated that soils artificially compacted to a pentrometer resistance of 2.0 MPa can reduce yields of transplanted cabbage by approximately 29%[34]. In Goldsboro, bulk density measured in LFM plots was significantly higher ($P = 0.008$) in NT sub-plots (1.47 g cm^{-3}) than in CT sub-plots (1.32 g cm^{-3}); however, this greater value would not be considered root restrictive[35].

Effects of SS on cabbage head weight

Cabbage head weight in Goldsboro was highest when cabbage was not preceded by SS, regardless of the tillage regime (Table 6). A similar, though less significant, trend was observed in CT cabbage at Reidsville (Table 7; $P = 0.050$). A negative correlation between head weight and accumulated SS cover crop biomass in tilled sub-plots at both locations (Goldsboro: $R = -0.72$, $P = 0.008$; Reidsville: $R = -0.65$, $P = 0.007$) suggests that the presence of incorporated SS residues negatively impacted cabbage growth. Because resource competition was not a factor in CT sub-plots, an allelopathic interaction may have been present. The allelopathic potential of SS and its effective exploitation for weed control are well documented[13,31,36]. Although allelopathic effects on transplanted crops have not been thoroughly investigated, incorporated SS residues have led to reduced growth of Eastern redbud transplants in pot culture[37].

Allelopathy may have also been a contributing factor to head weight reduction in NT cabbage at Goldsboro. Head weight was reduced in NT SS residue mulch compared to wheat straw mulch (Table 6). This finding is consistent with a greenhouse study in which SS surface residues reduced cabbage transplant dry weight compared to transplants grown under wheat straw[30]. However, the potential effects of allelochemical interference on cabbage head weight cannot be separated from the impact of SS re-growth in NT cabbage.

Summary

The results of this study suggest that SS can be managed as a single cutting hay crop without negatively impacting weed suppressive qualities of the cover crop. Cutting frequency following hay harvest is an important aspect of cover crop management for the optimization of weed suppression under NT conditions. Frequent cutting can lead to greater weed biomass in a subsequent cash crop. Cutting less frequently (e.g., each time the crop reaches 1.5 m) will provide residues of sufficient longevity and biomass to provide weed suppression of broadleaf weed species.

Increasing mowing frequency did not improve kill response of SS at either location in this experiment. Repetition of this experiment over multiple years at a single location would provide more conclusive data on kill response and subsequent cabbage growth. SS and other summer cover crops suited to dual application as hay exhibit high tillering and re-growth capacity, characteristics that contribute to poor mow kill response. Further investigation of strategies to enhance control of cover crop re-growth, including mechanical technologies (such as the addition of a crimper to rolling equipment), manipulation of cover crop management to improve kill response and application of herbicides approved for use in organic production, will aid further development of NT vegetable production with dual application cover crops.

In this study, SS introduced several competitive factors that negatively impacted the growth of cabbage in both NT and CT systems, including cover crop re-growth and possible allelopathy. This species may pose similar risks to other transplanted fall vegetables. Because of the potential biological and economic benefits of using this species as both hay and cover crop, future investigations may also seek to evaluate organic NT systems with SS for late-planted fall, over-wintering, or early spring crops that may mitigate the risks observed in this study. Repetition of this experiment for fall-planted vegetables with other cover crop species that could double as high-value organic hay crops but are killed more readily using mechanical means should also be conducted.

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A technique for assessing environmental impact risks of agricultural systems

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Abstract

Conventional agriculture often aims to achieve high returns without allowing for sustainable natural resource management. To prevent environmental degradation, agricultural systems must be assessed and environmental standards need to be developed. This study used a multi-factor approach to assess the potential environmental impact risk of six diverse systems: five production systems and a successional system or abandoned agronomic field. Assessment factors were soil quality status, amount of pesticide and fertilizer applied and tillage intensity. The assessment identified the best management practices (BMP)–conventional tillage system as a high-risk system mostly because of extensive tillage. The certified organic system was also extensively tilled and was characterized by P build-up in the soil, but performed well based on other assessment factors. Conversely, the BMP–no tillage and the crop–animal integrated system were characterized as low risk mainly because of reduced tillage. The paper discusses assessment strengths and weaknesses, ways to improve indicators used, and the need for additional indicators. We concluded that with further development the technique will become a resourceful tool to promote agricultural sustainability and environmental stewardship and assist policy-making processes.

Key words: environmental impact assessment, environmental risk indicators, agricultural production systems, soil quality, large-scale systems experiment, best management practices, farming systems

Introduction

Conventional agriculture was not traditionally associated with conservation and sustainable resource management. This has resulted in escalating environmental degradation and growing social realization that current agricultural systems must develop strict environmental standards rather than prioritizing on economic returns. As a result, there is much emphasis on alternative farming systems designed to decrease environmental harm caused by conventional farming[1].

Currently, a great body of literature exists on the quantification of environmental impacts and sustainability of conventional and alternative agricultural production systems[1–6]. System environmental performance is difficult, if not impossible, to evaluate directly because of various constraints. Studies generally assess system performance using a pre-chosen set of related indicators that are easily measured. Several indicators are preferred because of their sensitivity to change as a function of time and land management. Indicator selection criteria, proper methodologies and validations have also been widely addressed[7]. Individual indicators often do not provide an exhaustive vision of reality or complete information on the environmental risk of a system, as they tend to concentrate on a single criterion. Therefore, assessment results will likely be biased when limited criteria are used. Many researchers propose the use of multiple indicator measurements for a valid assessment[3,5,6,8].

The criteria for indicator selection cover a broad range of aspects that are not all equally achievable. Nevertheless, most researchers agree that an indicator should be scientifically founded, easy to interpret, responsive to changes related to human activities and able to show trends over time[9–12]. It should also provide a representative picture of

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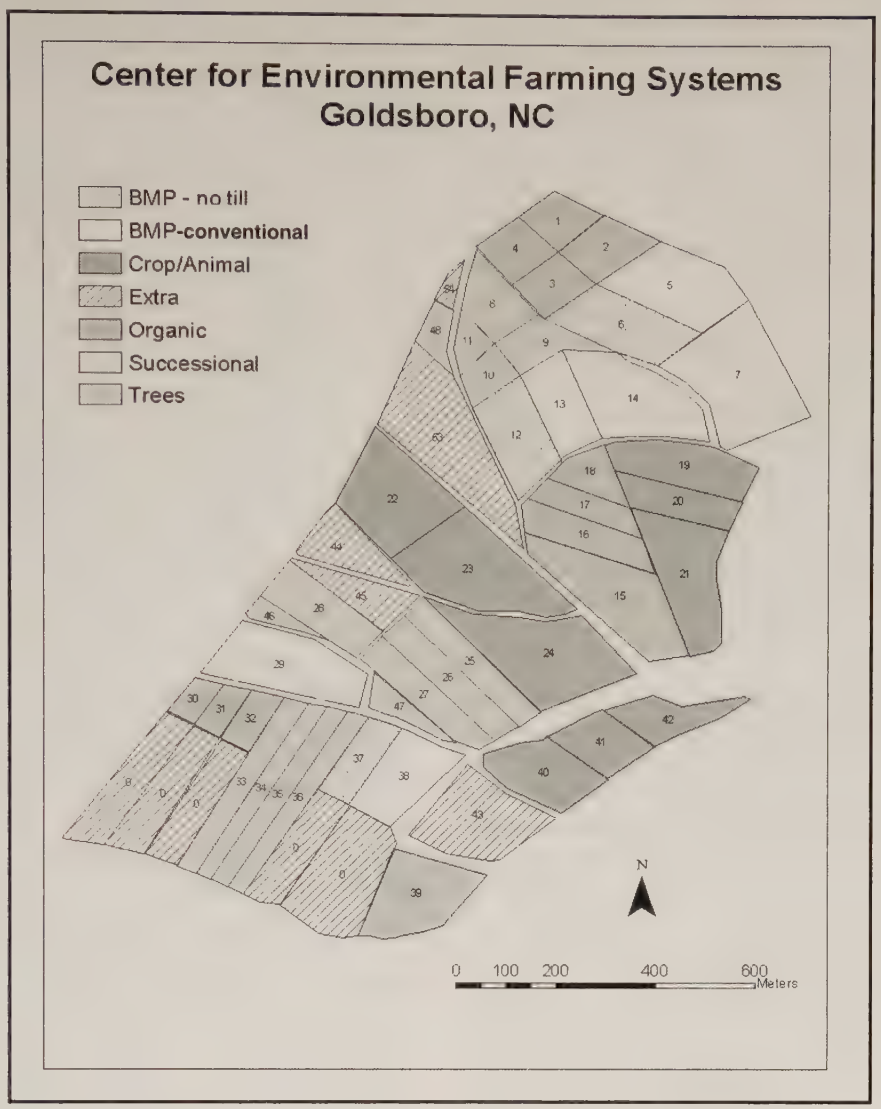

Figure 1. Experimental layout of the Farming Systems Research Unit study at the CEFS, Goldsboro, NC.

reality and be measurable at a reasonable benefit–cost ratio. Furthermore, an indicator may be meaningful only if a reference or target value exists based on empirical evidence[13]. Such a value should always be determined in the context of a current problem or situation. Indicators could be developed at the plot, field, farm, village, community, watershed, regional or national level. The level at which indicators should be applied depends on the problem and on data availability.

The objective of this study was to test an assessment that integrates multiple factors into single score of environmental risk and to employ a web-graph to display and interpret system differences.

Materials and Methods

This study used data collected from experimental plots of a long-term systems study, the Farming Systems Research Unit (FSRU) (Fig. 1), at the Center for Environmental Farming Systems (CEFS), Goldsboro, North Carolina. CEFS, established in 1994, is a partnership between the North Carolina Department of Agriculture and Consumer Services, North Carolina State University and North Carolina A&T State University. The center is dedicated to research on farming systems that are environmentally, economically and socially sustainable. FSRU addresses various issues relevant to long-term agricultural sustainability in North Carolina.

The FSRU experiment

FSRU is an 81-ha long-term field experiment with five systems and three replications (Fig. 1). Systems are conventional best management practices including conventional tillage (BMP/CT) and no-tillage (BMP/NT), a certified organic system (COS), an integrated crop–animal system (CAS), a successional (abandoned agronomic field) system (SUS) and a plantation forestry system (PFS). Experimental plots vary in size from 1.2 to 3.8 ha, depending on the landscape and the size of the block replicate.

Table 1. Vegetation grown in each system from 1999 through 2007 at the Farming Systems Research Unit at the Center for Environmental Farming Systems (CEFS), Goldsboro, NC.

	Production system[1]					
Year	**BMP/CT**	**BMP/NT**	**COS**	**CAS**	**PFS**	**SUS**
1999	Corn		Soybeans	Corn		
2000	Peanuts		Potatoes[2]	Soybeans		
2001	Cotton		Cabbage	Cotton		
2002	Corn		Corn	Corn	Black	Abandoned
2003	Peanuts		Soybeans	Peanuts	walnut	field
2004	Corn		Corn	Potatoes[2]		
2005	Corn		Corn	Pasture[3]		
2006	Sorghum		Soybeans	Pasture[3]		
2007	Soybeans		Soybeans	Pasture[3]		

[1] BMP/CT, best management practice–conventional tillage; BMP/NT, best management practice–no-tillage; COS, certified organic system; CAS, integrated crop–animal system; PFS, plantation forest system; SUS, successional system.
[2] Sweet potatoes.
[3] Warm-season switchgrass (*Panicum virgatum*), big bluestem (*Andropogon geradii*), eastern gamagrass (*Tripsum dactyloides*) and cool-season tall fescue (*Festuca arundinacea*).

Soils have been intensively mapped and digitized using GPS and GIS, and sampling was done on the 'diagnostic' soil type of each block to minimize soil type variability. Mueller et al.[14] provide a full description of FSRU.

Table 1 lists vegetation grown in each system since FSRU began in 1998. The two BMP systems predominate among farmers in the area, representing a standard for comparison. They are characterized by management practices commonly used by regional growers, such as annual crops and short rotations. Crops are regularly scouted for pests, and pesticides are applied only when economically justified. CAS represents a 15-year rotation of crops and livestock, mainly dairy steers. COS employs unique experimental approaches to nutrient management and pest control and provides critical information that helps growers' transition into organic production. Appropriate sivicultural practices are used in PFS under the production of black walnut (*Juglans nigra* L.). SUS represents an abandoned agronomic field allowed to succeed naturally since 1998. It serves as a control for the evaluation of farming effects.

Indicators framework

Knowledge of potential effectors will determine a suitable set of indicators and therefore increases assessment reliability. For example, an assessment that includes nutrient movement below the root zone needs to consider multiple variables including fertilizer type, rate and type of tillage practice used. In general, a multiple indicators approach needs to be implemented for an unbiased assessment.

Although this study focused on system environmental impact risks, we also determined yield index values to assess system productivity. The environmental impact risk assessment was based on soil quality status, amount of pesticide and fertilizer and tillage intensity. While many studies of this nature assessed single systems from different fields, our study was conducted on a single field having a large-scale, long-term, replicated experiment with very diverse systems. The final approach of the assessment was to integrate indicators and graphically delineate the overall system risk.

Crop yield. Because system crop rotations differed, a normalization procedure was done to compare yield data. In years where at least two systems had the same crop, we divided each yield measurement by the highest crop yield observed in the same year. The calculated ratios, ranging from 0 to 1, were used as productivity index values and allowed for system comparisons.

Soil quality. The soil management assessment framework (SMAF) developed by Andrews et al.[15] was used to assess soil quality. SMAF uses a system of decision rules to identify a set of soil properties as soil quality indicators. It allows selection of specific indicators based on the primary management goal for each specific site, and makes adjustments for climate, crop rotation, tillage practices, assessment purpose and inherent soil properties. Soil properties are transformed into unitless scores based on site-specific algorithmic relationships to soil functions. Finally, scores are averaged to produce a single index of soil quality.

Soil physical, chemical and biological properties measured in fall 2007 were used in SMAF. Properties were available water holding capacity (AWHC), soil bulk density (Db), aggregate stability (AS), soil pH, soil phosphorus (soil P), total organic carbon (TOC), microbial biomass carbon (MBC), soil metabolic quotient (qCO_2) and potentially mineralizable nitrogen (PMN). These properties were measured from soil core samples collected from the upper 7.6 cm in the five geo-referenced sampling points within the diagnostic soil of each experimental plot. For AWHC, undisturbed cores (7.6 cm in diameter, 7.6 cm in length) were slowly water saturated, placed in a low-pressure outflow

system[16] and desorbed to soil water potential of −10 KPa to determine field capacity. Bulk soil samples collected adjacent to the soil cores were desorbed in a high pressure outflow system to a soil water potential of −1500 KPa to determine permanent wilting point. Cores were then oven dried at 105°C to determine bulk density[17]. AS was measured using the wet sieving procedure[18] on air-dried aggregates of size 2.00–4.75 mm in diameter. Soil P was measured using the Mehlich-3 extraction method and pH using a 2 : 1 soil : water ratio. For MBC, field moist soil was sieved through a 3-mm sieve, immediately stored in sealed plastic bags at 4°C and within 1 week of sampling the chloroform fumigation-direct extraction procedure[19] was used. Total carbon was measured by combustion using a Perkin-Elmer 2400 CHN analyzer (Perkin-Elmer Corp., Norwalk, Conn.). PMN was determined using the anaerobic incubation method[20]. Soil respiration measurements were made at each geo-referenced sampling point using the closed-chamber technique[21] and used to determine qCO_2; the proportion of soil respiration and MBC.

Analysis of variance was conducted on the soil property data and on property score values to test for system differences. The pair comparison test used was Fisher's protected least significant difference. Results from the analysis of variance and pair comparison tests were interpreted at the 5% level of probability.

Pesticides. Pesticide risk assessment is complex because of the multidimensional nature of pesticide impacts. Pesticides are strictly regulated in the United States through a complex system that leads to product registration and regulations. During the registration process, the US Environmental Protection Agency (EPA) evaluates general, technical and safety information to approve product label and Material Safety Data Sheet (MSDS). The label and MSDS follow established uniform standards for describing potential risks and were used as our risk information source.

Product impact on water resources focuses on leaching and runoff losses, both determined by pesticide persistence, water solubility and mobility. Pesticide LD_{50} is the material dosage that would result in the death of 50% of a population of test species under standard conditions. Expressed as milligrams per kilogram of body weight it represents the acute effects of solids and liquids that are swallowed or affect the skin. We applied a measure proposed by Nelson and Bullock[22], the number of LD_{50} doses applied per hectare, to represent a level of pesticide acute human risk.

The pesticide Groundwater Ubiquity Score (GUS) was used to assess pesticide groundwater pollution risks[23]. Based on a pesticide's half-life and soil adsorption potential, GUS is determined as

$$\mathrm{GUS} = \log_{10}(t_{1/2}) \times [4 - \log_{10}(K_{oc})], \qquad (1)$$

where K_{oc} is a measure of soil adsorption of the pesticide, a high value indicating strong adsorption, therefore leaching is less likely. Pesticide half-life in soil ($t_{1/2}$), expressed in days, is the time necessary for transformation or degradation to one-half its previous concentration. It varies depending on soil moisture, temperature, oxygen status, microbial population, soil pH and other factors[24]. A GUS value of 2.8 or greater indicates high leaching potential, between 1.8 and 2.8 a moderate potential and less than 1.8 a low potential.

Fertilizer. Fertilizer N and P can have adverse environmental effects when excessively applied. For example, excessive N and P losses can result in the euthrophication of surface and coastal waters[25]. Our assessment rationale for fertilizer use was based on the amount of fertilizer N and P applied; i.e., less of an environmental impact as fertilizer N and P use is reduced. Fertilizer indicator values were determined as the average amount ($kg\,ha^{-1}$) of fertilizer N and P used in each system across all years (1999–2007).

Tillage. While tillage is required in some production systems, its effects on soil could be counterproductive. It reduces crop residue surface cover and thus increases aggregate breakdown, resulting in crusting and reduced infiltration[26]. Conversely, conservation tillage systems, systems with tillage practices that leave 30% or more of the soil surface covered by crop residues at planting, can increase soil organic matter content, improve soil quality, increase rainfall capture and reduce runoff[27–29]. Tillage indicator values were determined as the average number of tillage operations (e.g., plowing, chiseling, disking and cultivating) across years.

Determination and integration of index values

As mentioned previously, soil quality index values were determined by SMAF as the average of all soil property scores. For pesticides, fertilizers and tillage, indicator values were normalized using the procedure of Diaz-Balteiro and Romero[30] to produce aggregated index values. In general, the normalization used was

$$\bar{R}_{i,j} = 1 - \frac{R_{ij} - R_j^*}{R_{*j} - R_j^*} = \frac{R_{*j} - R_{ij}}{R_{*j} - R_j^*}, \qquad (2)$$

where $\bar{R}_{i,j}$ is the normalized value of system ith when evaluated with indicator jth, R_j^* is the best observed (ideal) value of indicator jth, R_{ij} is the outcome of system ith when evaluated with indicator jth before normalization and R_{*j} is the worst observed value achieved by indicator jth. In general, normalized indicator values are bounded between 0 and 1 with 1 being the 'ideal' situation and 'lesser than ideal' as the value becomes lower than 1. Aggregated index values for pesticides and fertilizers were calculated as the average of individual normalized pesticide and fertilizer indicators.

A web graph[31,32] was used to integrate all index values and delineate the overall risk in each system. Graph axes represent individual integrated risk indices. The external web of the graph represents the optimal condition for all indices. In other words, a system has less of an overall

Table 2. Soil properties measured in 2007 from the upper 7.5 cm in each production system.

Soil property[1]	Production system					
	BMP/CT	BMP/NT	COS	CAS	PFS	SUS
TOC (%)	0.93^{a}	1.11^{a}	1.09^{a}	1.06^{a}	0.90^{a}	0.99^{a}
MBC (mg kg^{-1})	365.2^{abc}	426.2^{ab}	362.9^{abc}	476.8^{a}	247.1^{c}	333.9^{bc}
PMN (g kg^{-1})	23.9^{ab}	18.5^{b}	33.9^{a}	22.8^{b}	16.3^{b}	22.5^{b}
pH	5.6^{c}	5.2^{a}	5.5^{a}	5.3^{a}	4.5^{b}	4.4^{b}
test P (mg kg^{-1})	207.8^{ab}	150.9^{bc}	323.9^{a}	67.8^{c}	159.2^{bc}	182.4^{bc}
$qCO_2 \times 10^2$	5.4^{ab}	3.7^{b}	5.5^{ab}	4.6^{b}	4.8^{b}	4.7^{b}
Db (g cm^{-3})	1.29^{cd}	1.50^{ab}	1.23^{d}	1.58^{a}	1.45^{b}	1.40^{bc}
AWHC (g g^{-1})	0.127^{b}	0.107^{bc}	0.150^{a}	0.096^{c}	0.100^{c}	0.100^{c}
AS (%)	29.6^{c}	63.9^{ab}	41.4^{bc}	58.2^{ab}	66.6^{a}	66.6^{a}

[1] For each soil property, production system means having the same letter in common are not significantly different at the 5% level of significance as indicated by Fisher's Protected LSD test. TOC, total organic carbon; MBC, microbial biomass carbon; PMN, potential mineralizable nitrogen; test P, extractable phosphorus; qCO_2, metabolic quotient; Db, soil bulk density; AWHC, available water holding capacity; AS, aggregate stability.

environmental risk as its web spreads more toward the outer boundary of the graph.

Results

Soil quality

No differences in soil properties were found between systems with the data collected when the study began in 1998 (baseline data – not shown). We point out that the soil quality differences presented with the data collected in fall 2007 are differences that developed over a period of 9 years. The differences observed during the first few years may not have been as large. Also, with one assessment date available, it is difficult to speculate how soil quality conditions changed over the study period.

System differences were found for all soil properties except for TOC (Table 2). MBC was highest in BMP/NT, CAS COS and BMP/CT and lowest in PFS and SUS. The qCO_2, which reflects the intensity of organic matter decomposition, was highest in COC and BMP/CT and lowest in BMP/NT. The higher decomposition activity in COS and BMP/CT was likely due to the increase availability of organic matter sources like crop residues and organic fertilizer, which were tilled into the soil. Residues in the other four systems predominate at the soil surface and therefore decompose at a slower rate. Soil P and PMN followed the same system trend as qCO_2. The greater PMN in COS and BMP/CT indicates greater availability of organic N for microbial use, which also explains the greater decomposition activity.

Soil pH values were higher in the four agronomic systems (COS, BMP/CT, BMP/NT and CAS) and lowest in the two non-agronomic systems PFS and SUS. These differences are likely related to differences in organic matter dynamics and microbial activities. The highly diverse group of broadleaf plants and grasses that grow in SUS produce large plant biomass and thatch residue amounts. During the decomposition of this material acid, functional groups are released from which H^+ ions dissociate. Also, the carbonic acid released from microbial respiration accumulates with time acidifying the soil. In addition, grasses in these two systems with their massive root system likely produced a significant amount of carbonic acid from root respiration.

Table 3. Soil property scores and soil quality index (SQI) obtained with the soil management assessment framework (SMAF) using the 2007 soil property data.

Soil property[1]	Production system					
	BMP/CT	BMP/NT	COS	CAS	PFS	SUS
TOC	0.90	0.97	0.96	0.88	0.91	0.95
MBC	0.93	1.00	0.97	0.99	1.00	0.99
PMN	0.98	0.92	1.00	0.83	0.87	0.98
pH	0.96	0.89	0.96	0.94	0.91	0.90
test P	0.44	0.86	0.12	1.00	0.66	0.45
qCO_2	1.00	1.00	1.00	1.00	1.00	1.00
Db	0.99^{a}	0.82^{b}	0.99^{a}	0.65^{c}	0.92^{ab}	0.97^{a}
AWHC	0.68	0.61	0.75	0.58	0.59	0.66
AS	0.93	1.00	0.97	0.99	1.00	0.99
SQI	0.90	0.93	0.88	0.91	0.91	0.91

[1] For Db, production system means having the same letter in common are not significantly different at the 5% level of significance as indicated by Fisher's Protected LSD test. No system differences were found for other soil property scores.

Soil bulk density was lowest in the tilled COS and BMP/CT systems and highest in the untilled CAS and BMP/NT systems. The higher Db in the untilled systems developed naturally by the settling and consolidation of soil. The baseline Db measured when the study began in 1998 was 1.36 g cm^{-3}.

Overall score values for TOC, MBC, PMN, pH, qCO_2 and AS were mostly greater than 0.90 indicating that in each system these properties were adequate (Table 3). Lower score values and system differences were obtained for soil P, Db and AWHC. The score values of 0.12 for COS and 0.44 for BMP/CT indicate excessive soil P levels.

Table 4. Pesticide risk indicator values for each production system averaged across crops and for each crop averaged across systems. For each pesticide risk factor, the higher the indicator value, the higher the risk.

	Acute[1] human risk	Chronic[2] human risk	Surface[2] water risk	Groundwater[3] risk
System				
BMP/CT	9.20	1.08	1.83	1.87
BMP/NT	9.81	1.07	1.74	1.88
CAS	4.99	0.58	1.01	1.55
Crop				
Corn	1.20	0.25	2.03	2.12
Cotton	23.46	1.58	0.00	1.89
Peanuts	25.97	3.06	2.33	1.97
Sweet potatoes	16.76	0.50	0.33	1.80
Sorghum	0.44	0.00	2.00	1.64
Soybeans	0.20	0.50	0.72	1.51
Pasture	0.02	0.00	0.07	0.93

[1] Acute human risk is a sum of LD_{50} doses (the presented values are in 1000 doses) from all pesticides applied per year.
[2] Chronic human and surface water risks are measured as the number of pesticides with high risk applied per year.
[3] Groundwater risk is an average GUS of pesticides applied per year.

For Db, the lowest score value was obtained with CAS, the system with the highest bulk density of $1.58\,g\,cm^{-3}$. Studies have found that for the type of soils found at the study site, sandy loam to loamy sands, a bulk density of $1.60\,g\,cm^{-3}$ or greater will limit root growth[33,34].

Pesticides

Results from the pesticide assessment are presented in Table 4. The system data are means across years and crops while the crop data are means across years when that specific crop was planted. No pesticides were applied in COS, SUS and PFS; therefore, pesticide indicator values equal zero. The two BMP systems had the highest values of all indicators. The CAS system resulted in somewhat lower risks because no pesticides were added in pasture years (2005–2007).

For the crops considered, the acute human risk was highest for cotton and peanuts, the chronic human risk was highest for peanuts, the surface water risk was highest for corn and peanuts. The groundwater risk was moderate for most crops except for soybeans and pasture which had low values of risk.

Fertilizer

SUS and PFS are not listed in Table 5 since no fertilizers were added in these systems. In COS, turkey litter was used as source of fertilizer while commercial fertilizers were used in the two BMP systems and in CAS. The two BMP systems and COS received the most N while COS received the most P. Therefore, CAS has a lower N risk while all systems except COS have low P risks. The amount of turkey litter applied that met crop N requirements in COS resulted in excess P applications. The N risk was highest with corn and sorghum and the P risk was highest with corn.

Table 5. Fertilizer risk indicators as amount (kg) of fertilizer N and P applied per hectare in each system (averaged across crops) and in each crop (averaged across systems).

	N	P
	$kg\,ha^{-1}$	
System		
BMP/CT	97.5	26.4
BMP/NT	108.7	15.7
COS	101.3	104.8
CAS	77.5	11.3
Crop		
Corn	171.1	82.6
Cotton	55.5	15.5
Peanuts	4.4	0
Sweet potatoes	32.5	27.3
Sorghum	110.1	0
Soybeans	74.2	17.5
Pasture	0	0

Table 6. Tillage risk indicators as the number of tillage practices (NTP) performed in each system (averaged across crops) and in each crop (averaged across systems).

System	NTP	Crop	NTP
BMP/CT	4.1	Corn	3.6
BMP/NT	0.2	Cotton	3.8
COS	7.0	Peanuts	3.7
CAS	2.7	Sweet potatoes	8.3
		Sorghum	2.3
		Soybeans	2.9
		Pasture	0.8

Tillage

The tillage indicator value was highest in COS and lowest in BMP/NT (Table 6). A post harvest pass with a disk unit was done in BMP/NT during peanuts years (2000 and 2003) resulting in the 0.2 indicator value. More tillage was done in COS because of its requirements of primary tillage (chisel plowing), secondary tillage (disking), creation of raised beds during cabbage and sweet potato years and cultivation for weed control. Tillage in BMP/CT and in CAS each year consisted of chisel plowing followed by disking several times until a smooth seedbed was achieved. The indicator value was lower in CAS because no tillage operations were conducted during pasture years.

Table 7. Environmental impact risk index values for each assessment factor in each production system.

System	Soil quality	Pesticide	Fertilizer	Tillage
BMP/CT	0.90	0.62	0.70	0.45
BMP/NT	0.93	0.61	0.69	0.97
COS	0.88	1.00	0.60	0.07
CAS	0.91	0.75	0.79	0.64
PFS	0.91	1.00	1.00	1.00
SUS	0.91	1.00	1.00	1.00

Index values

Resulting index values are shown in Table 7. Soil quality index values did not differ between systems, averaging 0.91. This high value indicates that, based on the soil properties considered in the assessment, the overall soil quality in each system was adequate. This does not mean that all soil properties in each system were within the 'ideal' range. As discussed earlier, some system properties were less than ideal and others were adequate with varying trends between systems. However, the average of property scores produced similar system soil quality index values and reflected adequate soil quality overall.

Pesticide index values were slightly lower in the two BMP systems compared with CAS where less pesticide was used. More fertilizer was used in COS and less in CAS as reflected by the respective index values of 0.60 and 0.79, but unlike in other systems, no commercial fertilizers were used in COS. The more tillage practices used in COS resulted in an index value of 0.07, while BMP/NT resulted in the highest 0.97 value.

The web graph (Fig. 2) illustrates individual risk indices and the overall multi-index assessment for each system. The tillage risk was highest with COS and BMP/CT, pesticide risk with the two BMP's, fertilizer risk with COS and no risk was associated with the soil quality factor. The two systems with the smallest web were COS and BMP/CT. Hence, the highest overall environmental impact risks are associated with these two systems. Conversely, there are lower risks with PFS and SUS, the two systems having the largest web. The two agronomic production systems with the lowest potential impact were web portrayed by BMP/NT and CAS. As illustrated in the graph, the productivity among systems was similar.

Discussion

We used a multi-factor approach to assess the potential environmental impact risk of six systems: five production systems (four agronomic and one planted trees) and a successional system or abandoned agronomic field. The assessment outcome is based on agronomic practices used and resulting soil conditions. For an overall system assessment, individual indicators are averaged into a single index value and a web graph is constructed. The major advantage of a web graph is that the overall system impact risk can be easily interpreted by the size of the web where the individual factor index values are also presented.

The assessment identified COS and BMP/CT as the two systems with the highest environmental risk mostly because they had the highest use of fertilizers and tillage. This does not imply that these two systems are environmentally unsound, but that potential risk factors need to be well managed to avoid adverse environmental effects. For example, when poultry litter is used as the nutrient source in the COS system its application rates are based on the nitrogen needs of the crop, but poultry litter also contains large amounts of P. Since crop P requirements are lower, an overapplication and build-up of P results. Therefore, the fertilizer guidelines for organic systems should be reconsidered to reduce P buildup. Equally, a positive assessment does not imply that the system is environmentally sound. BMP/NT and CAS were characterized as low-risk relative to the agronomic practices considered, but they could be environmentally unsound due to other factors. For instance, the consolidated soil condition in the pastured CAS, as indicated by the high bulk density, may limit infiltration and therefore increase the potential for fertilizer runoff.

The soil quality assessment in this study included measurements of physical, chemical and biological properties that reflect the status of multiple soil functions affecting productivity and environmental health. However, because SMAF is limited to the use of 11 soil properties, we were unable to make the assessment using specific properties that relate to limited functions in the coarse-textured soils of the Atlantic Coastal Plains region. For instance, these soils have low nutrient retention due to low clay and low organic matter contents. Hence, humic matter and CEC would be good indicators of nutrient retention and of the potential risk for nutrient movement below the root zone. Unwanted soil conditions like compacted soil zones that restrict crop rooting and water movement also develop due to poor soil management. A standard measurement that identifies this condition would also make the assessment more resourceful.

Five of the soil properties, TOC, MBC, soil P, PMN and AWHC, are used in SMAF on a weight basis rather than on a volume basis. Because Db changes as a function of soil management, the content of these measurements on a per soil volume basis will also change. This has been addressed in other studies and interpretation errors of 7–14% have been made when using soil data on a per weight basis[35].

The tillage assessment component can be improved by including measurements or estimations of surface crop residue cover which influences soil processes. As it is, two systems each with two tillage operations per year will have the same tillage index value regardless of the amount of surface residue left post tillage. One would expect more benefits in a system with significant surface residue cover (e.g., a conservation tillage system) compared with a

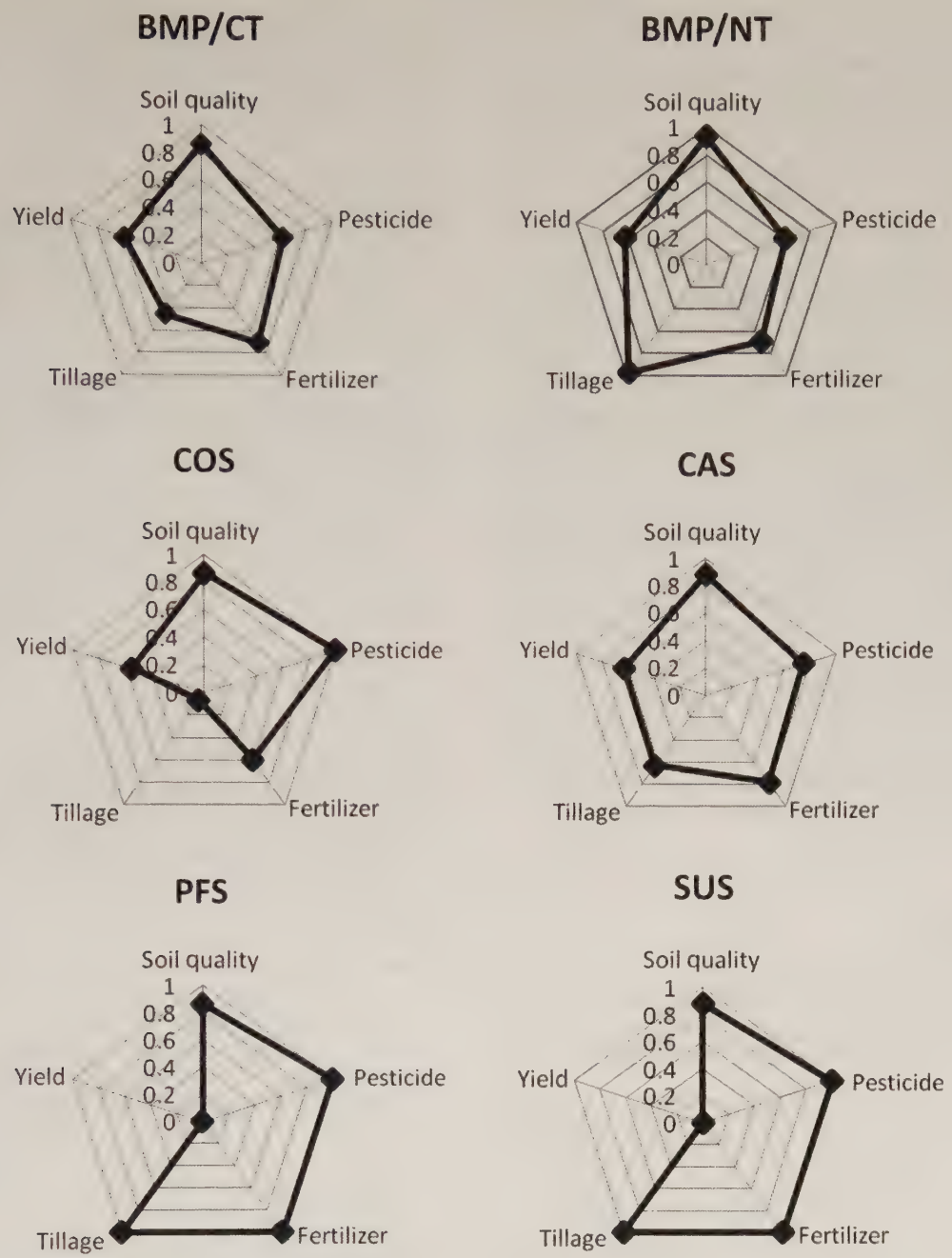

Figure 2. Web-graphed environmental impact risk index values for each system. BMP/CT, best management practice–conventional tillage; BMP/NT, best management practice–no-tillage; COS, certified organic system; CAS, integrated crop–animal system; PFS, plantation forest system; SUS, successional system.

system with no residue cover (e.g., a conventional tillage system).

The fertilizer factor can also be improved by adding an availability component. Fertilizer availability varies with chemical composition, fertilizer type (organic versus inorganic), release activity (slow versus fast) and application methods (split, banded, etc.). In general, fertilizer rates may be high for some systems but the environmental risk can be low if the above factors are considered in an effective management scheme.

Conclusions

Our approach to assess the potential environmental impact risk of integrated system production practices and resulting soil conditions was relatively simple and useful. For soil quality, SMAF is user-friendly and many soil properties used are relatively easy to sample and measure. The normalization and conversion procedures used on fertilizer, pesticide, tillage and yield scores were also simple. The display of integrated indicators in a web graph gives a clear system performance overview

and includes individual index values for system comparisons.

The methods used in this study can, to a certain degree, assist in the assessment of environmental impact risks of implemented agronomic practices. We recognized that for a more complete assessment additional environmental performance indicators need to be included and the indicators used can be improved. We would also like to point out that aggregated index values for soil quality, pesticides and fertilizers were calculated as the average of individual normalized indicators. Such an approach is informative about the general environmental impact trends, but with different set of relative weights assigned to individual indicators, aggregated results could vary. Indicator aggregation into some composite indices still remains a fruitful area for future research.

In addition, comprehensive assessments of this type should include economic and social indicators that would broaden the understanding of growers and determine any trade-offs between these indicators and environmental responsibility. Lastly, a comprehensive study should assess systems over time to account for the temporal variations of the highly dynamic indicators used. In general, we conclude that this assessment, with further development and the inclusion of additional indicators, can be a resourceful tool to promote agricultural sustainability and environmental stewardship and to assist policy-making processes.

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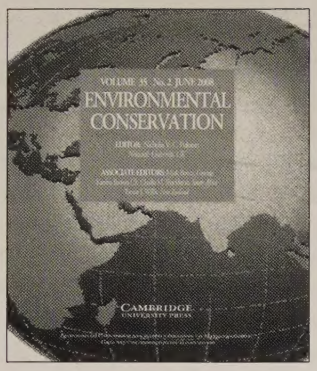

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